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Application of the DRAM software for the dynamic analysis of a linkage mechanism

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APPLICATION OF THE DRAM SOFTWARE FOR THE DYNAMIC ANALYSIS OF A LINKAGE MECHANISM

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ABSTRACT

This study provides the application of the DRAM software for the dynamic analysis of a linkage mechanism and presents a simplified version of the DRAM user manual. This user manual appears in appendix C.

The linkage mechanism which is used for the dynamic analysis consists of three rigid cranks, and two rigid couplers. Crank 2 of this mechanism is responsible for transfering motion to the other links. Kinematic and kinetic results by DRAM are compared with analytical results. Good agreement was observed.

Since the DRAM user guide is not easy to understand, it was necessary to write a user-friendly guide. Several types of kinematic and dynamic examples are included in this new manual. These examples demonstrate the usefulness and effectiveness of DRAM for the solution of progressively more complex problems. The new manual also provides the analytical solution of selected examples. The accuracy of the DRAM results are compared to the analytical results.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

The linkage mechanism is playing an important role in today's technology because of its simplicity. Mechanical engineers often adopt the linkage mechanism for the primary applications of various commercial softwares which analyze mechanical system response. DADS has recently been introduced in which a film follower mechanism is used as a sample example. In fact, this mechanism is little more than a simple application of the four bar linkage mechanism. DRAM, another popular commercial software package, also uses the linkage mechanism in many sample examples in the user manual. Hence, the linkage mechanism is one of the most commonly used and favorite mechanisms in today's changing technology.

DADS has been developed by Computer Aided Design Software, Inc. DADS performs 3-D dynamic, inverse dynamic, kinematic, and static analysis of physical systems operating through large displacements. Given geometries, mass properties, component characteristics, and system initial states, DADS automatically formulates and solves equations of motion, calculating positions, velocities, accelerations, reaction forces, and energies of the system and its components. The results are reported in tabular, curve, and animated fashion.

DRAM determines static equilibrium and time response (displacements, velocities, accelerations and reaction forces) of planar, multifreedom, rigid body mechanical systems (machinery, vehicles) which perform through large displacement. DRAM requires as data only a minimal definition of the mechanical system. It proceeds from this data to develop and numerically evaluate the system equations of motion, then reports the results as graphic terminal display or print-out summaries.

Several features have been incorporated into DRAM to account for the behavior of realistic machinery and vehicles. These are:

1 Representation of multi-degree-of-freedom (dynamic), constrained or unconstrained systems, including the zero degree-of-freedom (kinematic) system as a subset.

2 A library of force elements such as springs and dampers. Included in the library are modes of impact and Coulomb friction.

3 A library of motion generators (ideal motors) which describe time dependent motion of various elements.

4 User-specified force effects permitting representation of unusual or non-linear applied forces.

5 Surface-to-surface (high pair) contact.

Most commercial softwares have the ability to handle constant velocities as well as changing velocities, to perform a complete cycle analysis. However, sometimes it may be necessary to use special velocity input subroutines to perform the desired task. These subroutines must be written in an acceptable form specified by the software. Such is the case with DRAM.

In this thesis, the dynamic response of a rather complex linkage mechanism has been analyzed. In this study, both DRAM (Dynamic Response Of Articulate Machinery) and the analytical solution are utilized for the dynamic analysis of the linkage mechanism. DRAM computer graphics has also been generated. With the help of computer graphics, it is possible to display the motion of each link of the mechanism on the graphic terminal during the cycle.

Since the DRAM user guide is difficult to understand, it was necessary to develop a user-friendly guide to demonstrate the usefulness and effectiveness of DRAM for the dynamic analyses of mechanical systems. While developing a simplified version of the DRAM user manual, it was important to consider several different types of examples. The examples are presented in such a fashion that the reader's familiarity with the coding is built up in steps.

II. LITERATURE REVIEW

Every mechanical engineer has a general understanding of the principles of dynamics. However, the depth and breath of knowledge needed to accurately analyze complex, real-word problems, not to mention the tediousness of the calculations, is discouraging. Considering the limited time and budget available for most design projects, one should not be surprised that most design engineers typically do very little dynamic analysis themselves. Instead, they rely either on an analytical specialist or, more commonly, on the build-and-test method. Dynamic analysis has been the last of the major engineering methods to benefit from the computer's power.

Why has dynamic analysis, the link for all other methods, matured only recently? Generating the equations of motion required to simulate the dynamic operation of a mechanism is straightforward. The obstacle has been a quick, simultaneous solution to these equations at tiny intervals of time over the period covered by the analysis. To be useful in practice, the solution must be derived in an interactive time frame, i.e. one or tens or hundreds of seconds. Another reason for the late start of computer-aided dynamic analysis lies in graphics hardware.

The first general-purpose program to calculate the time response of multifreedom, constrained machinery undergoing large displacements was DRAM (Dynamic Response Of Articulated Machinery). This two dimensional program uses the tree-branch coordinate method to minimize computation time. Basically, this approach refers each successive part of the model to one or more preceeding parts, thus producing a matrix that is dense but greatly reduced in size. In addition to solving dynamic problems, DRAM is also capable of static and kinematic analyses.

The original version of the program was completed in 1969 at the University of Michigan under the direction of Milton Chace, MDI chairman, who was then a professor of mechanical engineering. DRAM is now marketed by Mechanical Dynamics Inc.

In 1973, Nicolas Orlandea wrote ADAMS (Automated Dynamic Analysis Of Mechanical Systems) for his doctoral thesis in mechanical engineering at the University of Michigan. ADAMS was designed as a three-dimensional, large displacement dynamic program that could also handle kinematics and statics problems. To solve the equations of motion, ADAMS uses a sparse matrix method. The matrix is larger than that in DRAM, but most of the variables have a coefficient of zero. A special solver algorithm maps out the matrix and eliminates unnecessary operations before ADAMS performs the actual computation. In practice this method has been shown generally to yield faster solutions than the tree branch approach.

Although DRAM and ADAMS are internally very different, they appear quite similar to the user. For both programs, the user must first break the mechanism down into its rigid bodies and then enter descriptions of these parts and their connections in the input data language. The input data format for ADAMS is quite similar to that for DRAM. The major difference lies in the additional information required to describe motion in three dimensions rather than two. ADAMS also offers a wide range of joints, with revolute, translational, cylindrical, spherical, universal, rack and pinion, and screw joints being available.

For many problems the systematic creation of input data is all that is required of the user. In other cases it is impossible to completely define the problem using the input language. For instance, DRAM provides only constant velocity and harmonic motion generators. To provide more flexibility, both programs allow the user to define forces, motion generators, and output requests through Fortran subroutines.

The increasing popularity of large displacement dynamics software is beginning to attract the attention of turnkey CAD suppliers, who are writing the interfacing software required for their systems. Among the first vendors to announce interfaces for ADAMS and DRAM are Applicon, Computervision, Control Data, Intergraph, McAuto, and Sperry. For the user of dynamics software, the interface eliminates the need to enter any geometric data; the basic part geometry created on the CAD system in earlier phases of design is transferred to ADAMS and DRAM. Additionally, the entry of data on constraints and forces is simplified by the use of menu commands.

Both ADAMS and DRAM can be run either interactively or in batch mode. The interactive mode is the more appropriate for the first run, because it allows the programs to check for input data errors. For later runs the user can switch to batch mode to minimize computing cost.

Some of the applications of ADAMS and DRAM can described as follows.

ADAMS is used primarily where the displacement and forces being studied are in three dimensional space. For example, the Chevrolet Engineering Center used the software to simulate the behavior of an entire automobile as it was driven over curbs, chuckholes, railroad ties, and other highway obstacles. Large displacement dynamic simulation of this kind permits determination of the highest reaction forces that components such as suspension bushings are likely to encounter during their lifetime. With these forces known, peak stresses can be determined through finite-element analysis.

The DRAM program performs two dimensional, planar simulations. These mechanical systems may not necessarily lie in a single plane. Rather, all points of interest lie in parallel planes as they move. These structures are represented as planar systems with top, side, or front views of the assembly. One of the industrial uses of DRAM was the analysis of a Deere and Co. spring reset plow that unhooks from embedded rocks. When the plow blade hits a rock, the mechanism receives the shock loading, permits the bottom to rise up over the obstacle, and then resets to normal operation. Computer simulation was used to design the links, stops, and springs, that permits the plow blade to escape a rock regardless of its depth or shape.

Recently, the dynamic analyses of systems is also done by the DADS (Dynamic Analysis and Design System) software. DADS has been developed by Computer Aided Design Software Inc. The Dynamic Analysis and Design System is a general purpose computer program which solves kinematic and dynamic analysis problems for a variety of real word systems. DADS builds a mathematical model of the real system to calculate the positions, velocities, accelerations, and reaction forces of the various components of the system. DADS performs 3-D dynamic, inverse dynamic, kinematic, and static analysis of physical systems operating through large displacements. DADS automatically formulates and solves equations of motion, calculating positions, velocities, accelerations, reaction forces, and energies of the system and its components.

Using DADS, the designer can simulate the behavior of a wide range of alternate designs without the expense of building and testing prototypes. DADS has a large library of mechanical elements containing various joints, constraints, and force elements. DADS has the following features:

1. Uses state-of-art numerical integration methods to provide better stability and efficiency.

2. Automatic removal of redundant constraints.

3. User friendly preprocessor.

4. Graphical postprocessor.

5. Complete planar analysis

6. User supplied subroutines.

7. Upward compatibility of the PC version to the more sophisticated mainframe version of DADS.

There are the number of instances where engineering time and money are very important in the analysis of problems. DADS is very useful in these situations. Some of the situations can be summarized as follows:

1. Where analysis is not done at all, or is done by hand, DADS can reduce the time and expense of doing the analysis manually, or make analysis feasible where it was not feasible before.

2. Where computer analysis of kinematics and large displacement dynamics is already being done by means of writing special programs, or by inserting equations of motion into programs, DADS's superior generality and ease of use can save time and money when analyzing complex system or when a large number of alternating designs must be evaluated.

3. Where another general purpose kinematic and large displacement dynamic analysis program is in use, there can be difficulties because some of those programs are restricted to solving either closed loop or open loop problems, or are suitable only for grounded body problems or only "free-free" problems. DADS is very general and easily solves all those classes of problems.

This thesis is concerned with the DRAM software only.

III. DESCRIPTION OF MECHANISM

The linkage mechanism presented in this study consists of six links and is a closed loop type mechanism. See figure 1. These six links form two loops. Each loop has four links. Figure 2 describes these loops with their assumed direction for the analysis. This mechanism has two types of links. Link 3 is a rigid link with a 120 degree angle between the two arms while the other links are of the straight rigid type. The intersection of link 3 and link 6 is a point whose motion is noncircular. Figure 1 describes the initial position of each link. The clockwise rotation of crank 2 generates the input motion for the respective links in the mechanism. The rest of the links have counterclockwise rotational motion. All angles and angular velocities measured in the counterclockwise direction are considered positive.

IV. COORDINATE SYSTEM

The analysis of this mechanism employs a right handed coordinate system. For DRAM analyses, two types of coordinate systems need to be used. The first coordinate system is called the local reference axis system, and describes the orientation of the link and the positions of the markers in the link. The orientation of the local reference axis is determined with respect to another coordinate axis system called the global coordinate axis

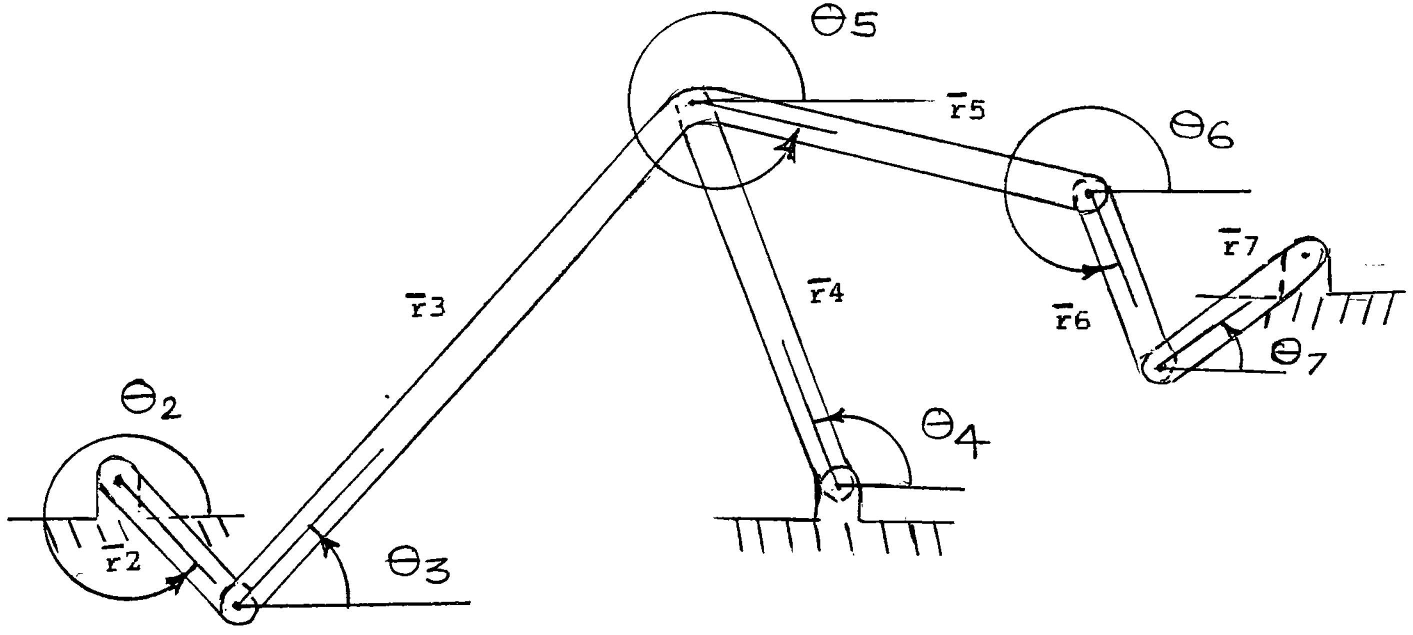

FIG. 1. : LINKAGE MECHANISM.

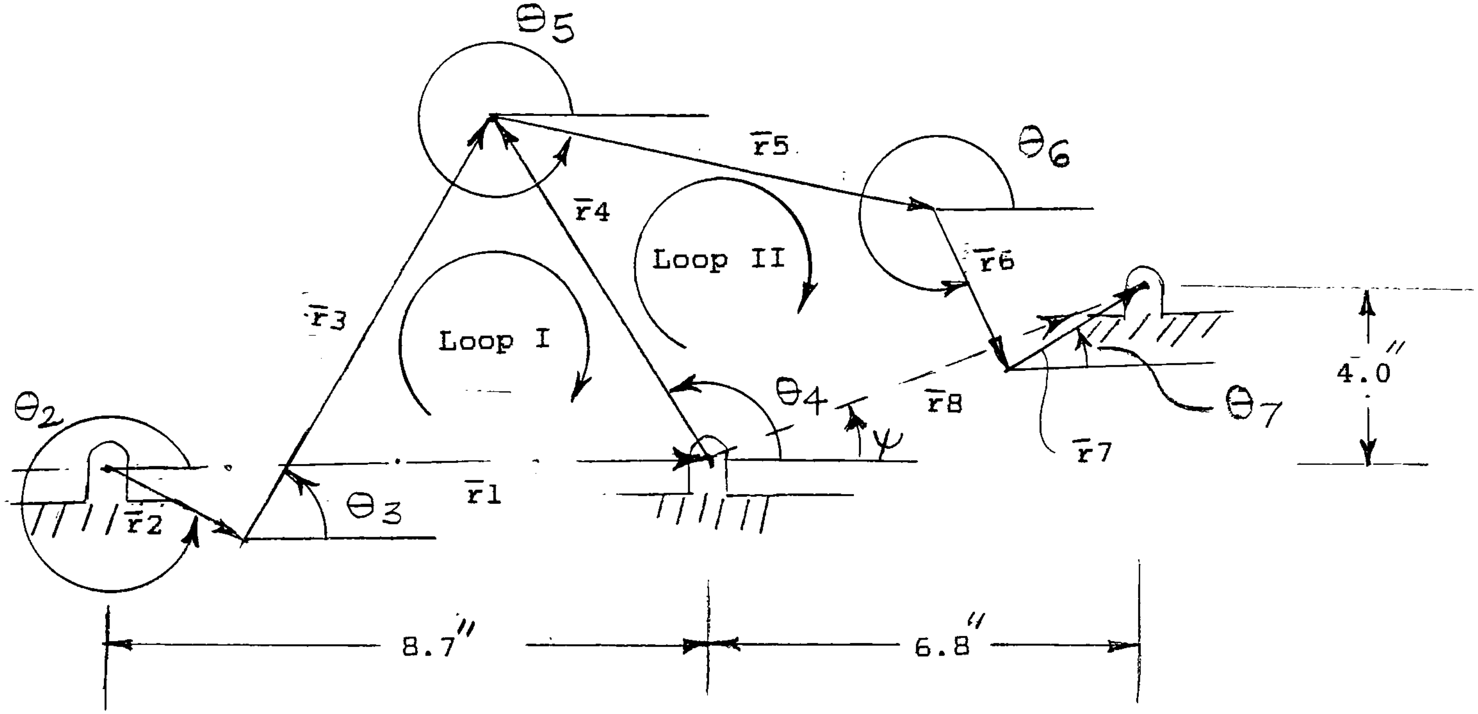

FIG. 2 : LINKAGE MECHANISM WITH THE POSITION VECTORS AND RESPECTIVE ANGLES.

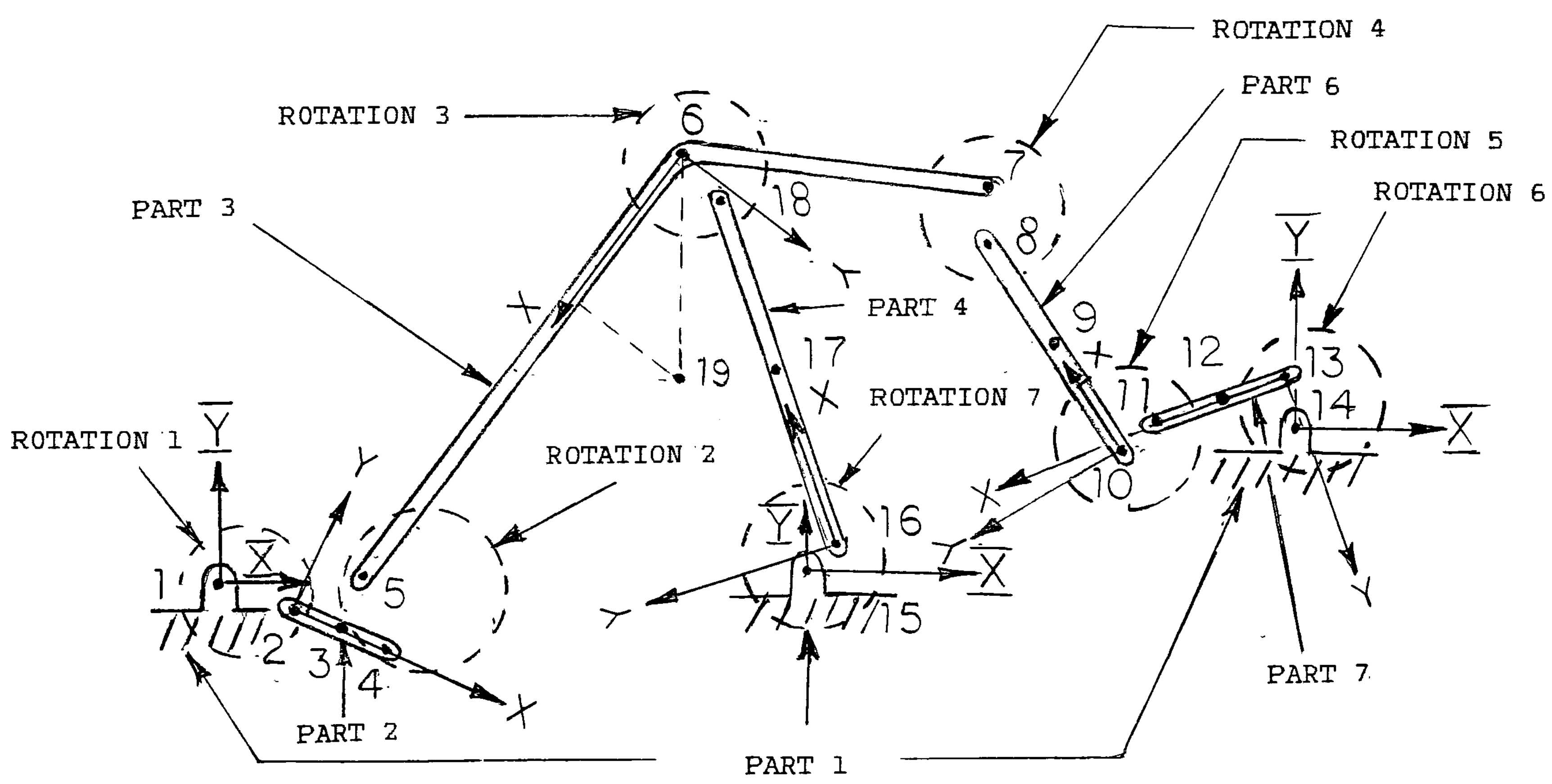

FIG. 3. : LINKAGE MECHANISM WITH THE MARKERS AND COORDINATE SYSTEMS (DRAM).

system. The global coordinate axis system is always attached to the fixed points of the mechanism. In the analytical solution, a simple right hand coordinate system has been used. Figure 2 and figure 3 show the selected coordinate systems for the analysis of the mechanism.

V. SELECTED INPUT DATA FOR DYNAMIC ANALYSIS

The following input data has been used in the analysis of the linkage mechanism:

Note that the link of lengths must be referred to the local reference axis system for DRAM. Refer to figure 3. Length of crank 2 (r2) = 2.7 inch., length of link 3 (arm-1)(r3) = 10.8 inch., length of link 3 (arm-2)(r5) = 7.0 inch. (for DRAM the length r5 is resolved into the x and y components such that x= -3.5, y= 6.0621778), length of link 4 (r4) = 6.8 inch., length of link 6 (r6) = 2.6 inch., length of link 7 (r7) = 1.4 inch. The distance between the rotational point of link 2 and link 4 is (r1=) 8.7 inch. The rotation point of link 7 is positioned $\bar{X}$ = 6.8 inch and $\bar{Y}$ = 4.0 inch from link 4. Angle theta 2 (T2) = 315 degree, angle theta 3 (T3) = 53.6465 degree., angle theta 4 (T4) = 93.2790 degree., angle theta 6 (T6) = -115.7399 degree., angle theta 7 (T7) = 13.5402 degree. Crank 2 is rotating with a constant velocity of 31.415927 rad/sec (1800 degree/sec)(cw). Weight of link 2 = 0.15 lbf, weight of link 3 = 0.3 lbf, weight of link 4 = 0.25 lbf, weight of link 6 = 0.12 lbf, weight of link 7 = 0.1 lbf. Mass moment of inertia of link 2 = 0.00094409 lbf inch. sec. sq, mass moment of inertia of link 3 = 0.02437009 lbf inch. sec. sq, mass moment of inertia of link 4 = 0.00998037 lbf inch. sec. sq, mass moment of inertia of link 6 = 0.00072108 lbf inch. sec. sq, mass moment of inertia of link 7 = 0.00018612 lbf inch. sec. sq. Note: Since DRAM automatically divides the values input for mass and mass moment of inertia by gc, the values of mass and mass moment of inertia used in the DRAM input data coding need be input in lbm units.

VI. MATHEMATICAL EQUATIONS OF THE ANALYSIS

Since the DRAM results obtained needed to be checked by generating an analytical solution, the complex variable method was adopted for the analysis. However, the same analysis can be done by using the vector method as well. These methods have been explained in "Kinematics And Dynamics of Machines" by Martin, G. H. To implement the complex variable method, the linkage mechanism was considered in two loops. Figure 2 shows the two loops of the mechanism along with the vector direction of each link in the respective loop.

The displacement, velocity and acceleration equations are summarized here and the complete derivation of these equations is given in appendix A.

First loop:

Displacement:

$$\bar{r}_2 \cos\theta_2 + \bar{r}_3 \cos\theta_3 - \bar{r}_4 \cos\theta_4 = \bar{r}_1 \quad ----(1)$$

$$\bar{r}_2 \sin\theta_2 + \bar{r}_3 \sin\theta_3 - \bar{r}_4 \sin\theta_4 = 0 \quad ----(2)$$

Velocity:

$$\bar{r}_2(-\sin\theta_2)\dot{\theta}_2 + \bar{r}_3(-\sin\theta_3)\dot{\theta}_3 - \bar{r}_4(-\sin\theta_4)\dot{\theta}_4 = 0 \quad ---(3)$$

$$\bar{r}_2(\cos\theta_2)\dot{\theta}_2 + \bar{r}_3(\cos\theta_3)\dot{\theta}_3 - \bar{r}_4(\cos\theta_4)\dot{\theta}_4 = 0 \quad ---(4)$$

Acceleration:

$$\bar{r}_2(-\cos\theta_2)(\dot{\theta}_2)^2 + \bar{r}_3(-\cos\theta_3)(\dot{\theta}_3)^2 + \bar{r}_3(-\sin\theta_3)\ddot{\theta}_3$$
$$-\bar{r}_4(-\cos\theta_4)(\dot{\theta}_4)^2 - \bar{r}_4(-\sin\theta_4)\ddot{\theta}_4 = 0 \quad -----(5)$$

$$\bar{r}_2(-\sin\theta_2)(\dot{\theta}_2)^2 + \bar{r}_3(-\sin\theta_3)(\dot{\theta}_3)^2 + \bar{r}_3(\cos\theta_3)\ddot{\theta}_3$$
$$-\bar{r}_4(-\sin\theta_4)(\dot{\theta}_4)^2 - \bar{r}_4(\cos\theta_4)\ddot{\theta}_4 = 0 \quad ------(6)$$

Second loop:

Displacement:

$$\bar{r}_4 \cos\theta_4 + \bar{r}_5 \cos\theta_5 + \bar{r}_6 \cos\theta_6 + \bar{r}_7 \cos\theta_7 = \bar{r}_8 \cos\psi \quad ---(7)$$

$$\bar{r}_4 \sin\theta_4 + \bar{r}_5 \sin\theta_5 + \bar{r}_6 \sin\theta_6 + \bar{r}_7 \sin\theta_7 = \bar{r}_8 \sin\psi \quad ---(8)$$

Velocity:

$$\bar{r}_4(-\sin\theta_4)(\ddot{\theta}_4) + \bar{r}_5(-\sin\theta_5)\dot{\theta}_5 + \bar{r}_6(-\sin\theta_6)(\dot{\theta}_6)$$
$$+\bar{r}_7(-\sin\theta_7)(\dot{\theta}_7) = 0 \quad -------(9)$$

$$\bar{r}_4 \cos\theta_4(\dot{\theta}_4) + \bar{r}_5 \cos\theta_5(\dot{\theta}_5) + \bar{r}_6 \cos\theta_6(\dot{\theta}_6)$$
$$+\bar{r}_7 \cos\theta_7(\dot{\theta}_7) = 0 \quad ----------(10)$$

Acceleration:

$$\bar{r}_4(-\cos\theta_4)(\dot{\theta}_4)^2 + \bar{r}_4(-\sin\theta_4)\ddot{\theta}_4 + \bar{r}_5(-\cos\theta_5)(\dot{\theta}_5)^2 + \bar{r}_5(-\sin\theta_5)\ddot{\theta}_5$$
$$+\bar{r}_6(-\cos\theta_6)(\dot{\theta}_6)^2 + \bar{r}_6(-\sin\theta_6)\ddot{\theta}_6 + \bar{r}_7(-\cos\theta_7)(\dot{\theta}_7)^2 + \bar{r}_7(-\sin\theta_7)\ddot{\theta}_7 = 0$$
$$-----(11)$$

$$\bar{r}_4(-\sin\theta_4)(\dot{\theta}_4)^2 + \bar{r}_4(\cos\theta_4)\ddot{\theta}_4 + \bar{r}_5(-\sin\theta_5)(\dot{\theta}_5)^2 + \bar{r}_5(\cos\theta_5)\ddot{\theta}_5$$
$$+\bar{r}_6(-\sin\theta_6)(\dot{\theta}_6)^2 + \bar{r}_6(\cos\theta_6)\ddot{\theta}_6 + \bar{r}_7(-\sin\theta_7)(\dot{\theta}_7)^2 + \bar{r}_7(\cos\theta_7)\ddot{\theta}_7 = 0$$
$$------(12)$$

The virtual work method has been used to find the torque input at link 2. The torque equation is summarized here and the complete analysis of the virtual work is given in appendix A.

$$T_{s2}\ddot{\theta}_2 = I_3\ddot{\theta}_3\dot{\theta}_3 + [I_4 + m_4(\bar{r}_4/2)^2]\ddot{\theta}_4\dot{\theta}_4 + I_6\ddot{\theta}_6\dot{\theta}_6 + [I_7 + m_7(\bar{r}_7/2)^2]\ddot{\theta}_7\dot{\theta}_7 + W_2\dot{x}_2 + (W_3 + m_3\ddot{x}_3)\dot{x}_3 + m_3\ddot{y}_3\dot{y}_3 + W_4\dot{x}_4 + (W_6 + m_6\ddot{x}_6)\dot{x}_6 + m_6\ddot{y}_6\dot{y}_6 + W_7\dot{x}_7 \quad ---(13)$$

A FORTRAN computer program was written to compute the angular displacement, velocity, and acceleration of the various links for a complete cycle of motion. The torque required at link 2 to drive the linkage through one complete cycle was also computed by the program.

VII. RESULTS AND DISCUSSION

Computer Graphics:

Schematic drawings of the linkage mechanism have been generated by DRAM's postprocessor on the Tektronix terminal. DRAM's ability to save the graphic information during a simulation, for subsequent analysis, is being utilized by means of the GRSAVE option in the input data coding. The computer graphics of the linkage mechanism was developed by writing a graphics program package in the input data coding. The various graphics statements used in the graphics program are explained in the examples of chapter 9 of " A simplified version of the DRAM user manual " in appendix C. Various commands have been used to display the computer graphics of the linkage mechanism on the Tektronix terminal. These commands are summarized in chapter 8 of " A simplified version of the DRAM user manual ".

Figure 4 shows a hard copy of the computer graphics of the mechanism that was obtained. Link 6 and link 7 of the mechanism are of interest during the analysis. Therefore, to identify the displacement of link 6 and link 7, an arrangement of the small circles have been made through the graphics program at each respective link. The displacements of other links could be identified in a similar manner.

Kinematics:

Since the linkage mechanism is of closed loop type, the system is simulated in the kinematic mode by DRAM. The input data errors such as the errors in lengths, angles,

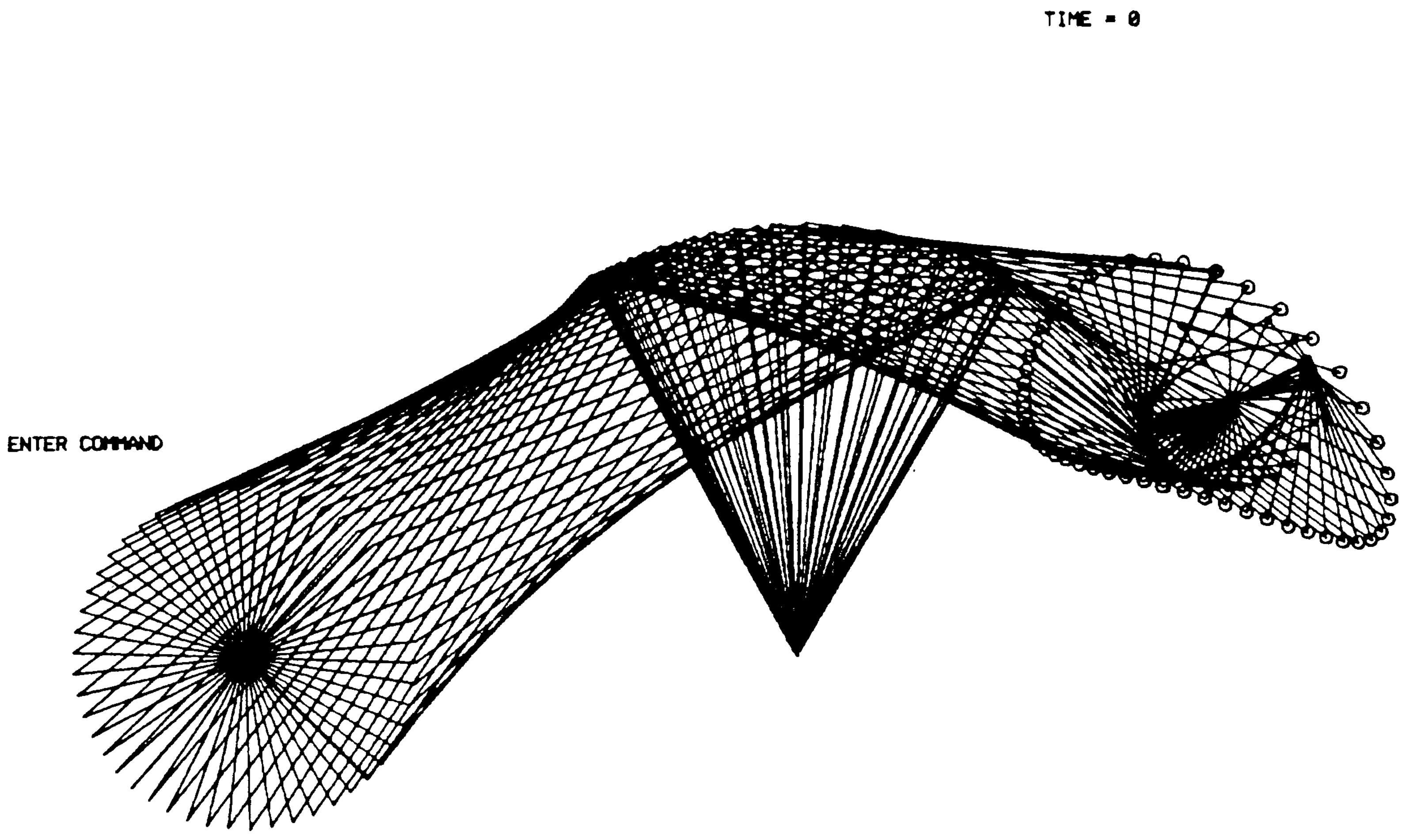

FIG. 4. : COMPUTER GRAPHICS.

etc. in the program was detected easily due to DRAM's ability to correct the initial input data. As result, the input data was checked, and corrected.

A complete description of the linkage mechanism was input to DRAM through the input data coding language. As mentioned earlier, link 6 and link 7 are of interest in this analysis. Their displacements, velocities and accelerations were determined by requesting these outputs in the DRAM request statements. Since the step size in the output statement of the input data coding is 50, the complete cycle analysis of the mechanism provides 50 values of each output request. The time interval of two consecutive output values is 0.004 second. However, the number of output values of each output request could be increased by increasing the steps. The values of all angles were output in degrees. They can be output in radians by using the RANGLE option in the output statement.

In order to check the DRAM results, an analytical solution was done with the help of a computer program. The calculated analytical results show a close match with the DRAM results. Further more, plots of DRAM results as well as plots of the analytical results by the DIS8 plotting software appear to be the same.

Figure 5 though figure 16 show the plots of the DRAM results and the analytical results. A comparison of figure 5 with figure 6 shows that the nature of these curves appears to be consistent. However, the plotted numbers of angular displacement of link 6 on the y axis of the DRAM

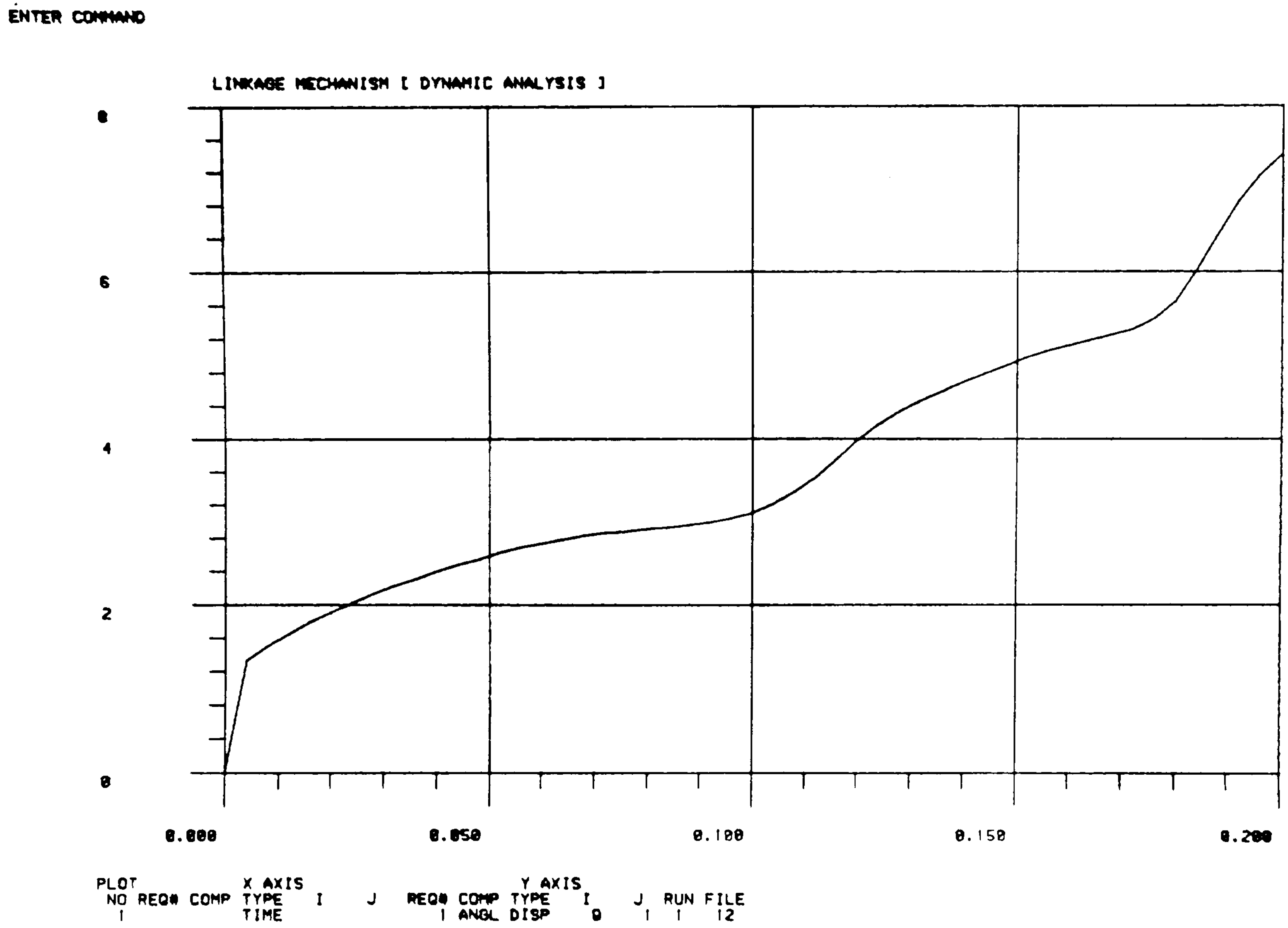

FIG. 5. : ANGULAR DISPLACEMENT OF LINK 6 (DRAM).

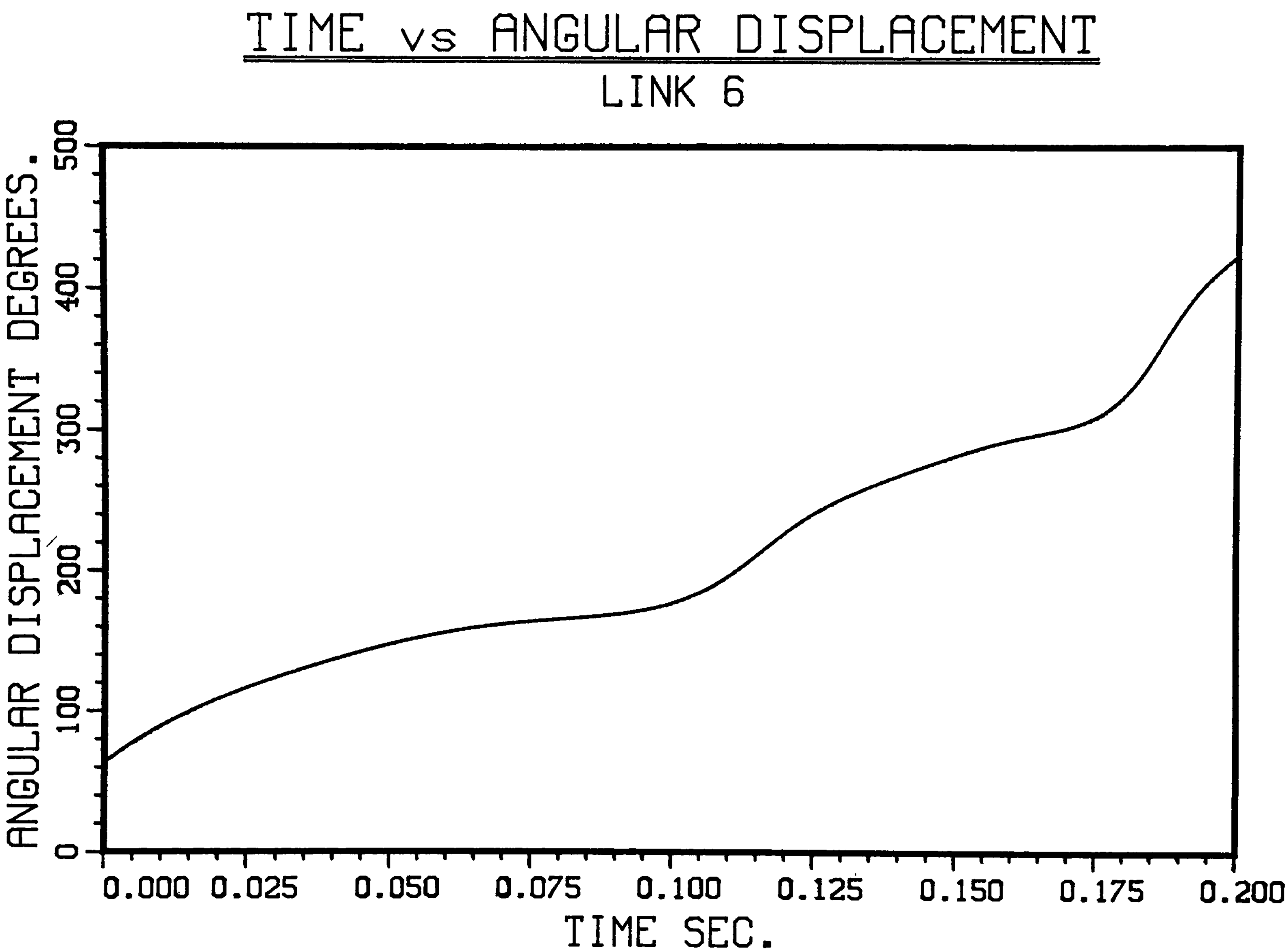

FIG. 6. : ANGULAR DISPLACEMENT OF LINK 6 (ANALYTICAL).

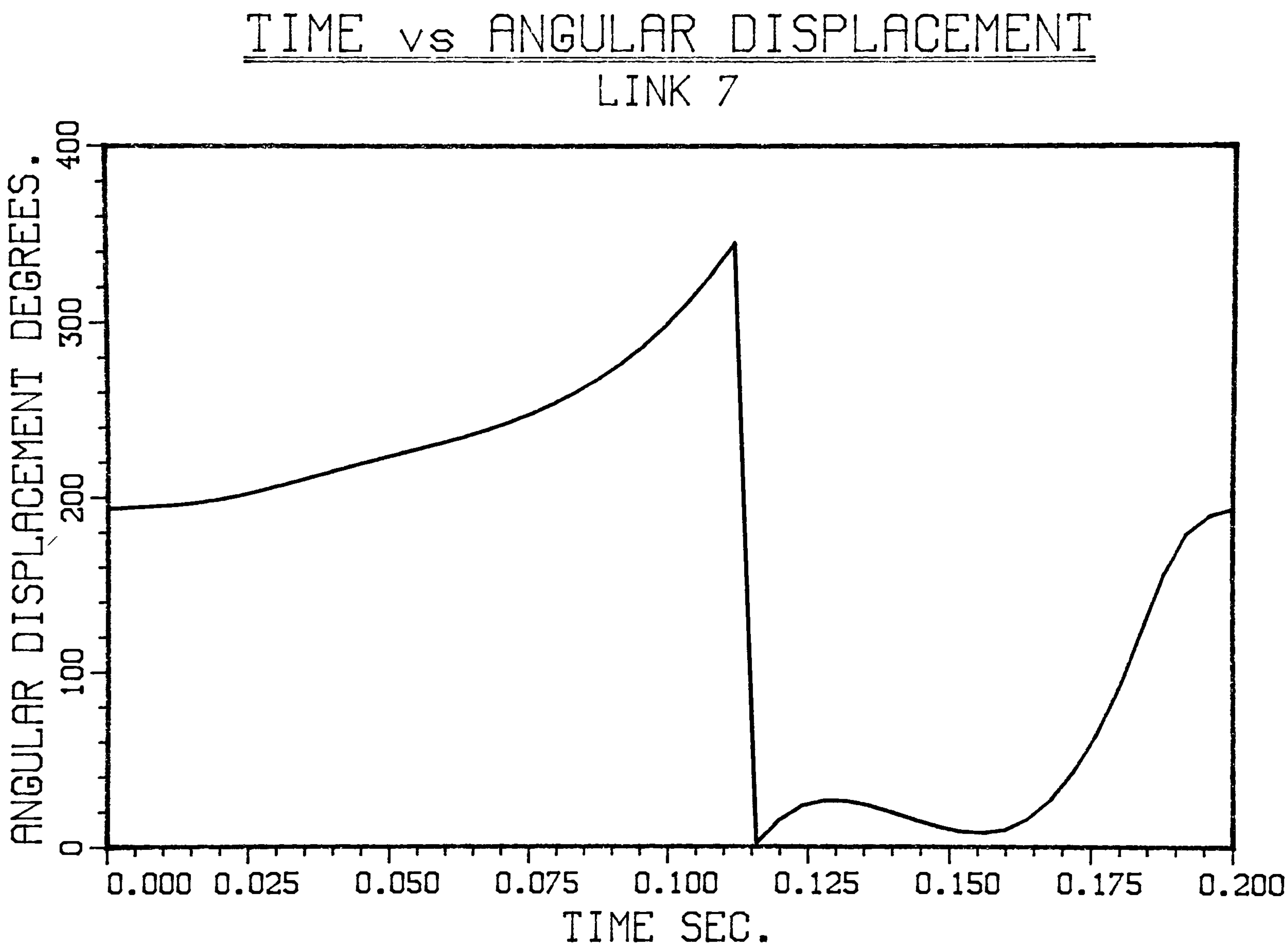

FIG. 7. : ANGULAR DISPLACEMENT OF LINK 7 (DRAM).

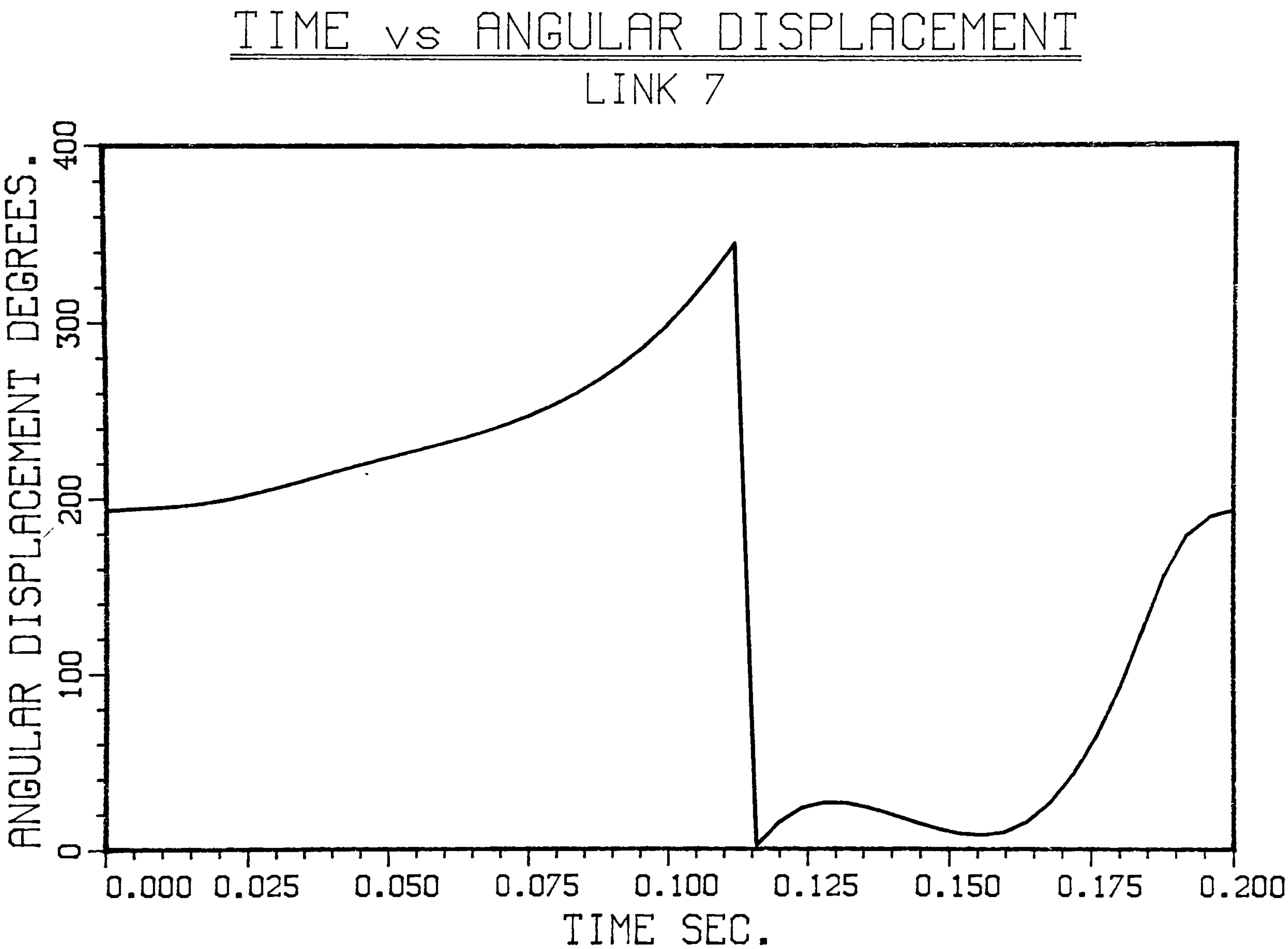

FIG. 8. ANGULAR DISPLACEMENT OF LINK 7 (ANALYTICAL).

ENTER COMMAND

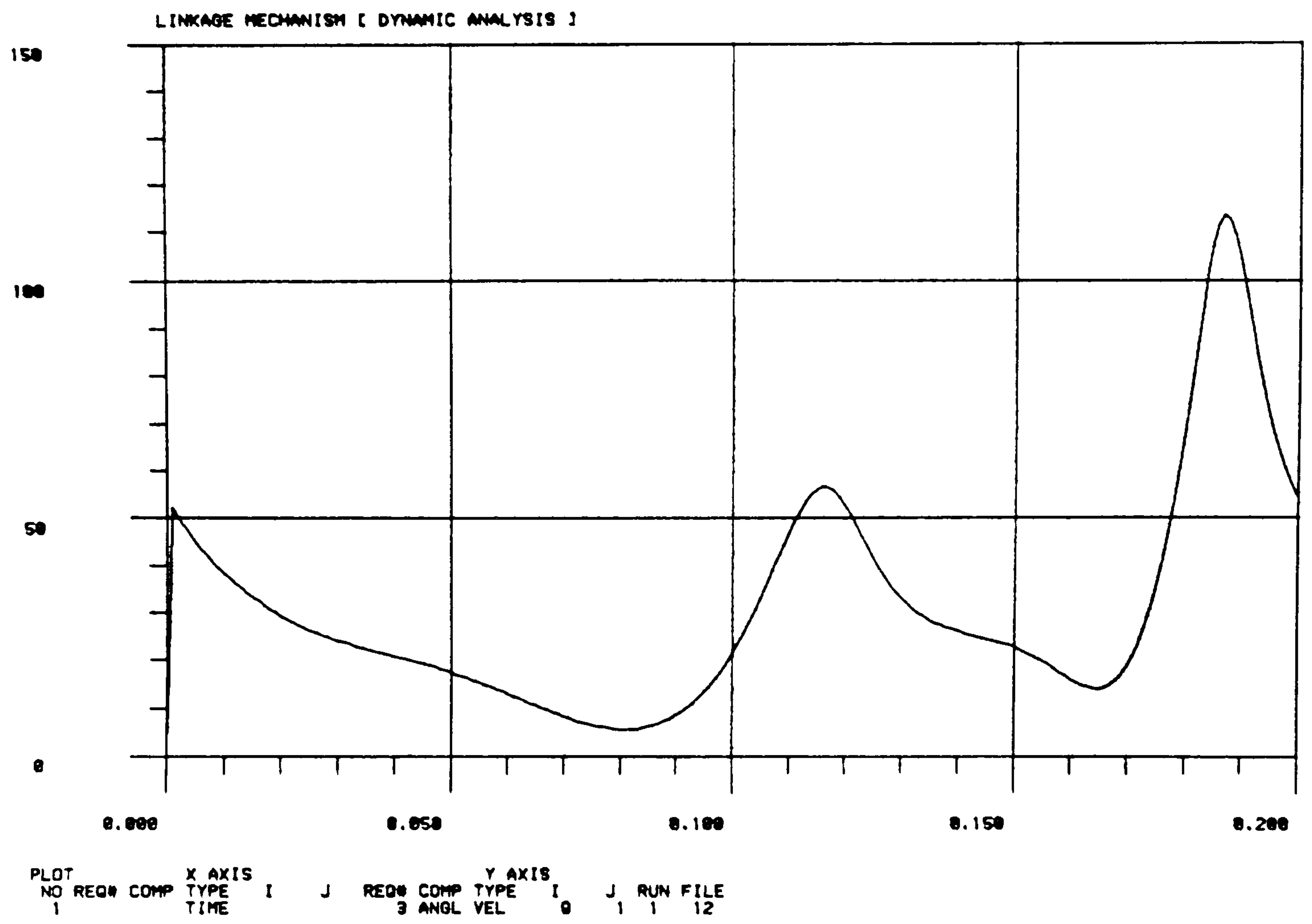

FIG. 9. : ANGULAR VELOCITY OF LINK 6 (DRAM).

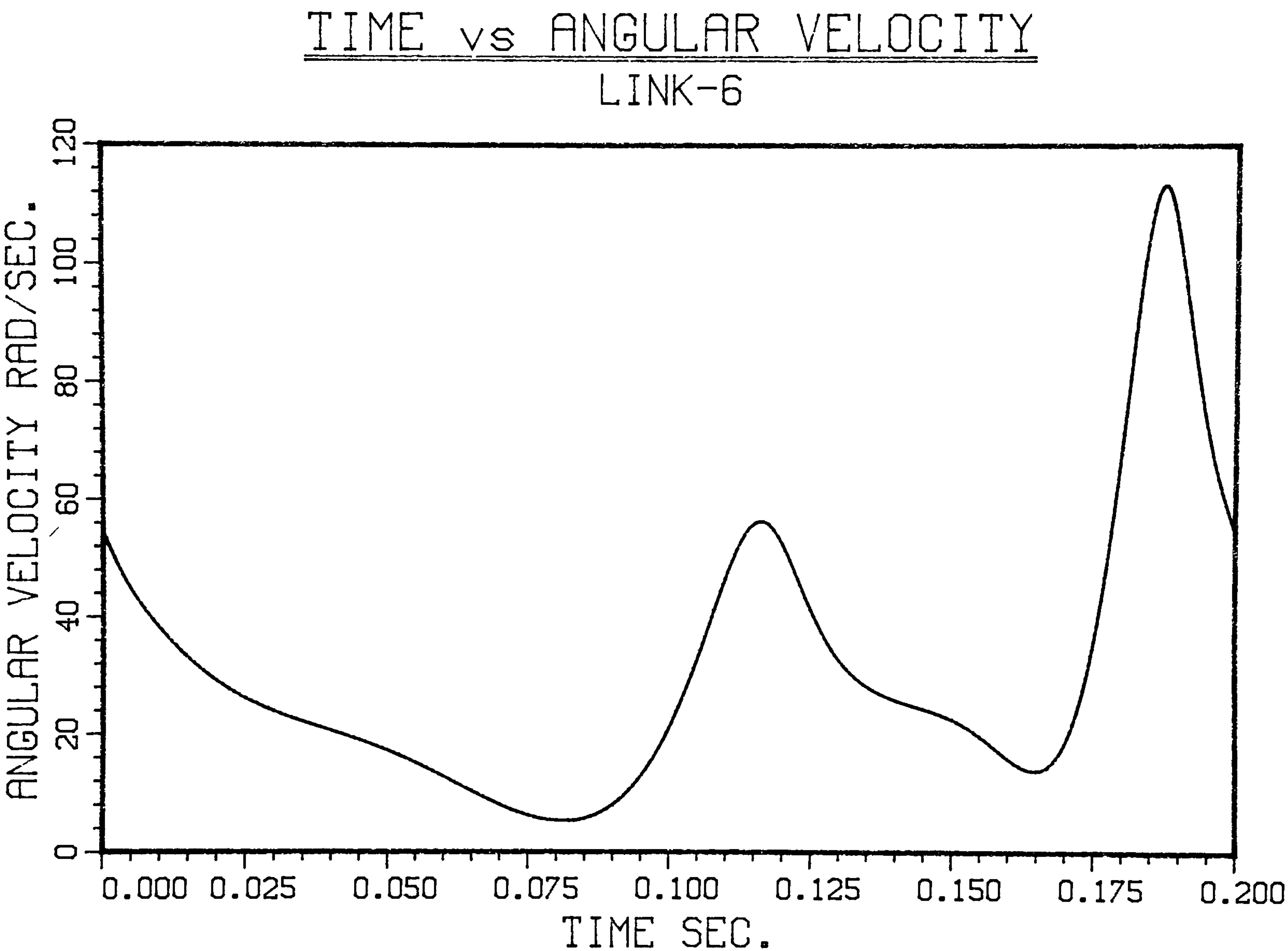

FIG. 10. : ANGULAR VELOCITY OF LINK 6 (ANALYTICAL).

ENTER COMMAND

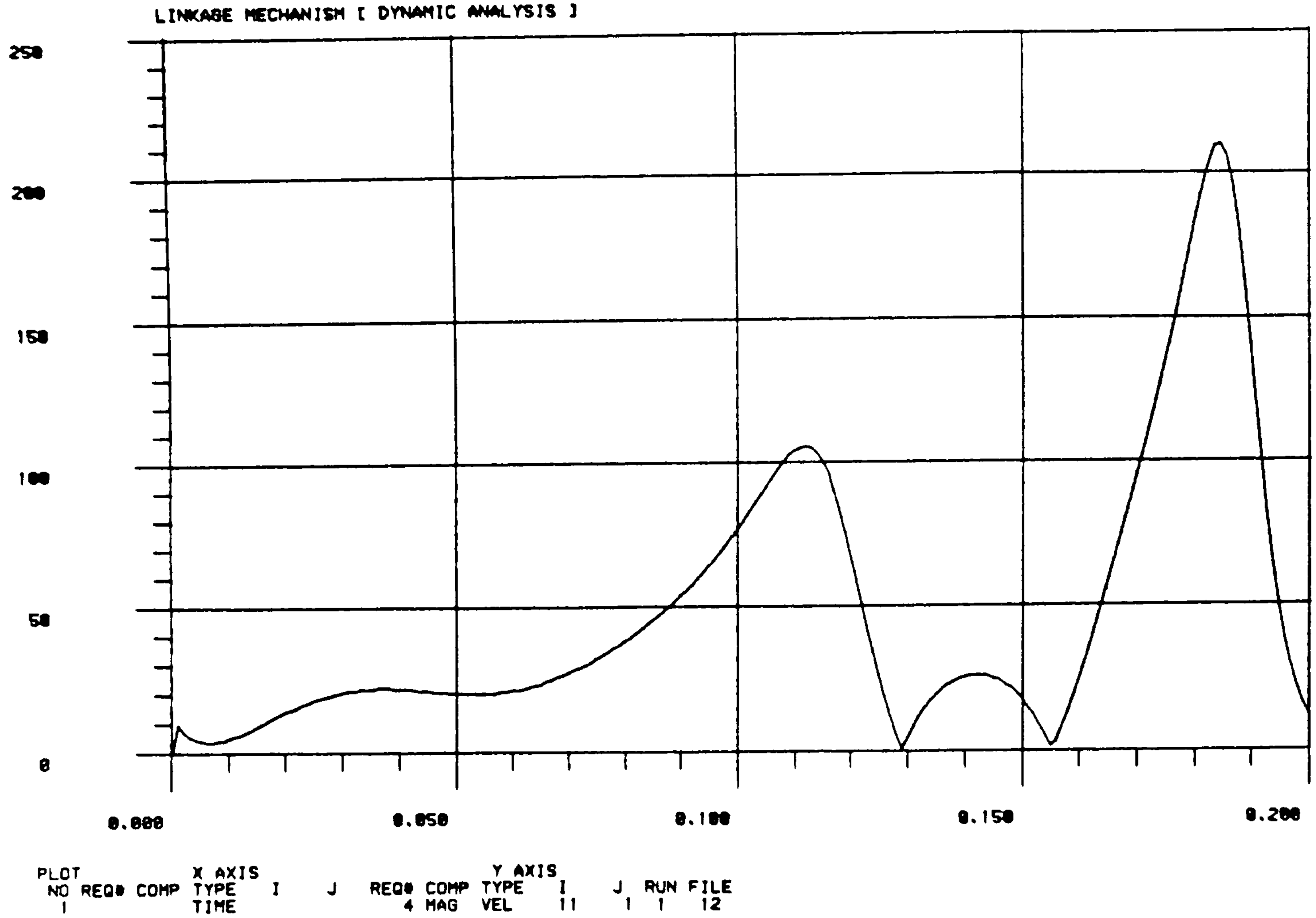

FIG. 11. : LINEAR VELOCITY OF LINK 7 (DRAM).

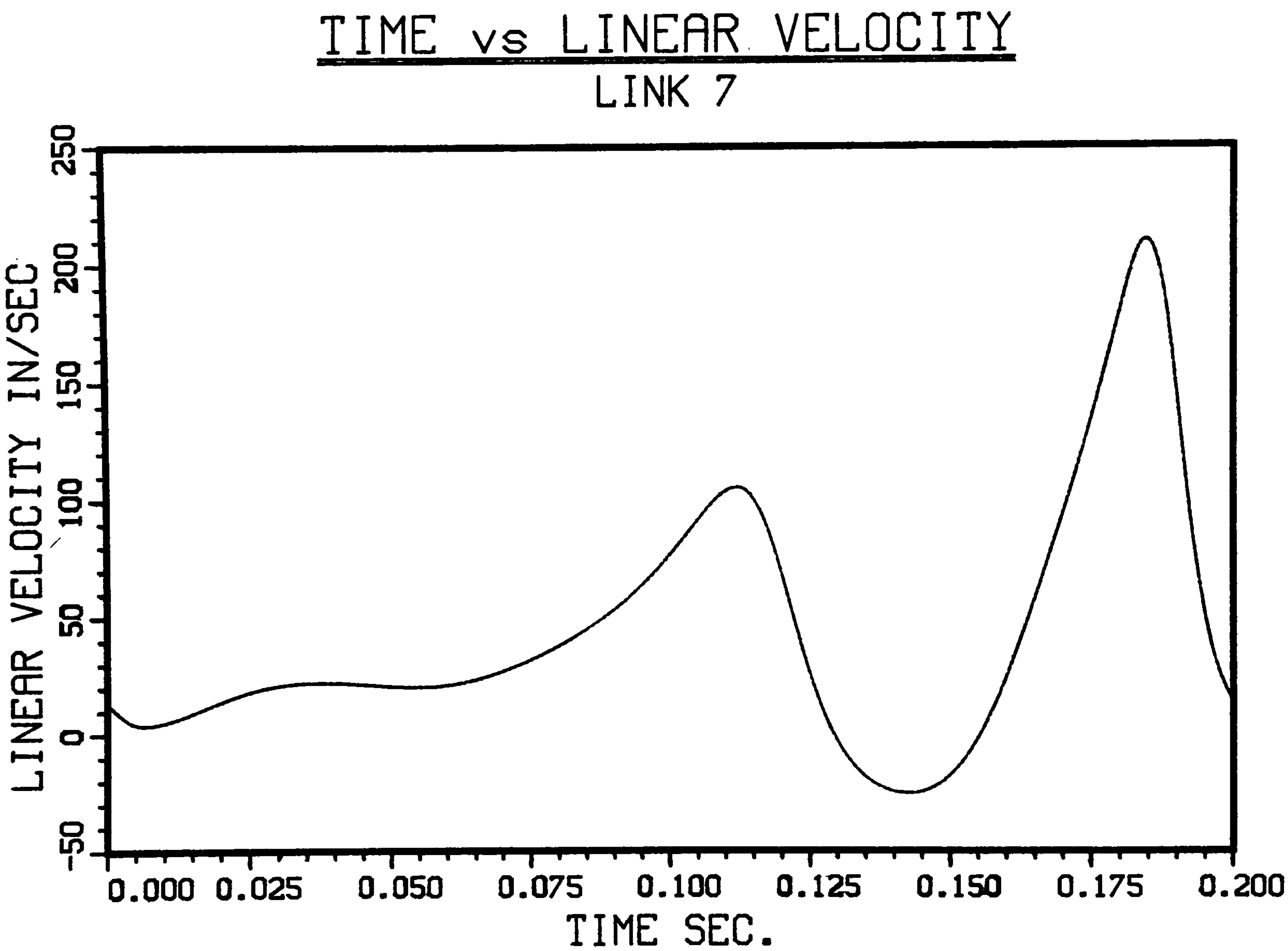

FIG. 12. : LINEAR VELOCITY OF LINK 7 (ANALYTICAL).

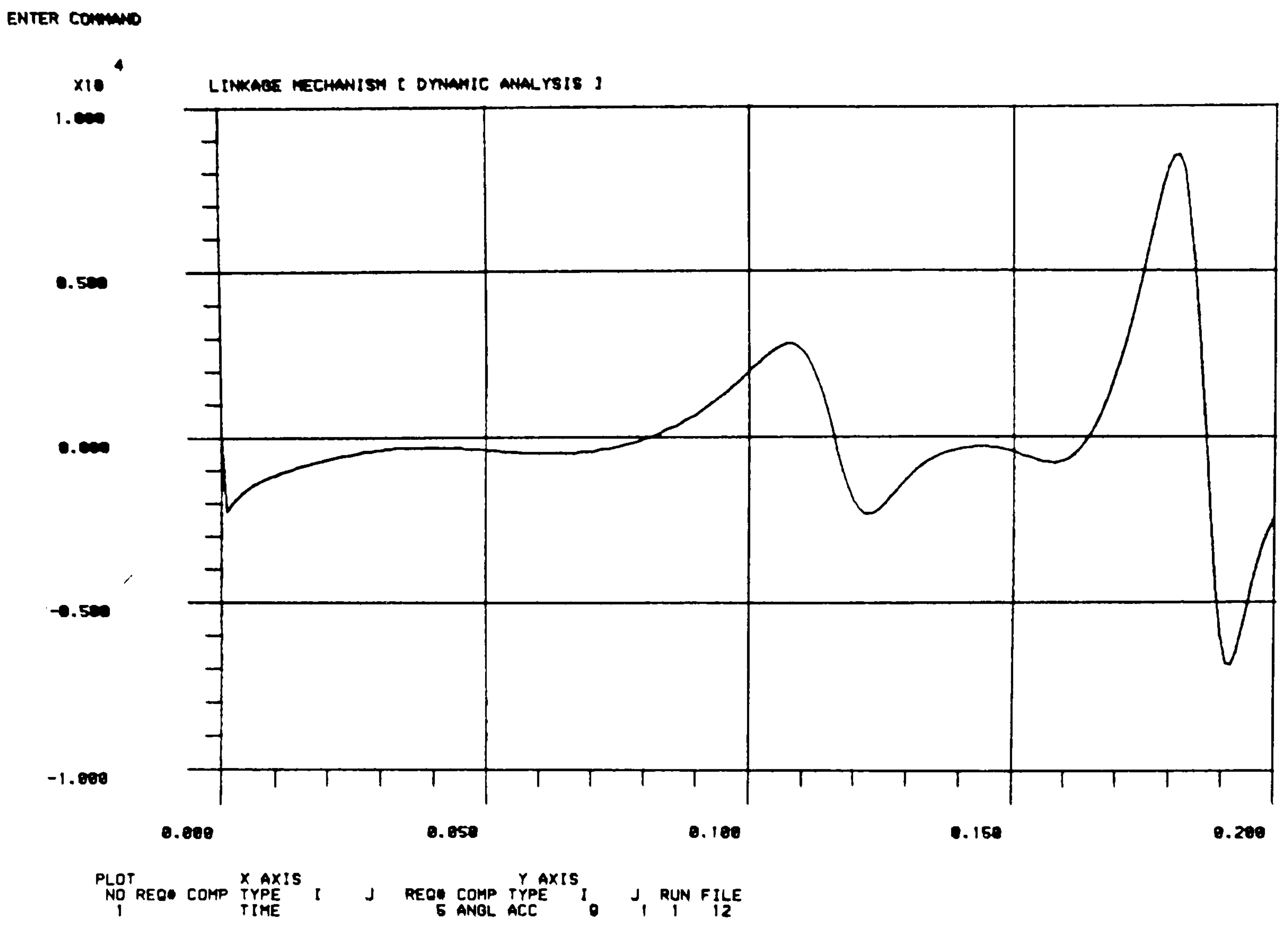

FIG. 13. : ANGULAR ACCELERATION OF LINK 6 (DRAM).

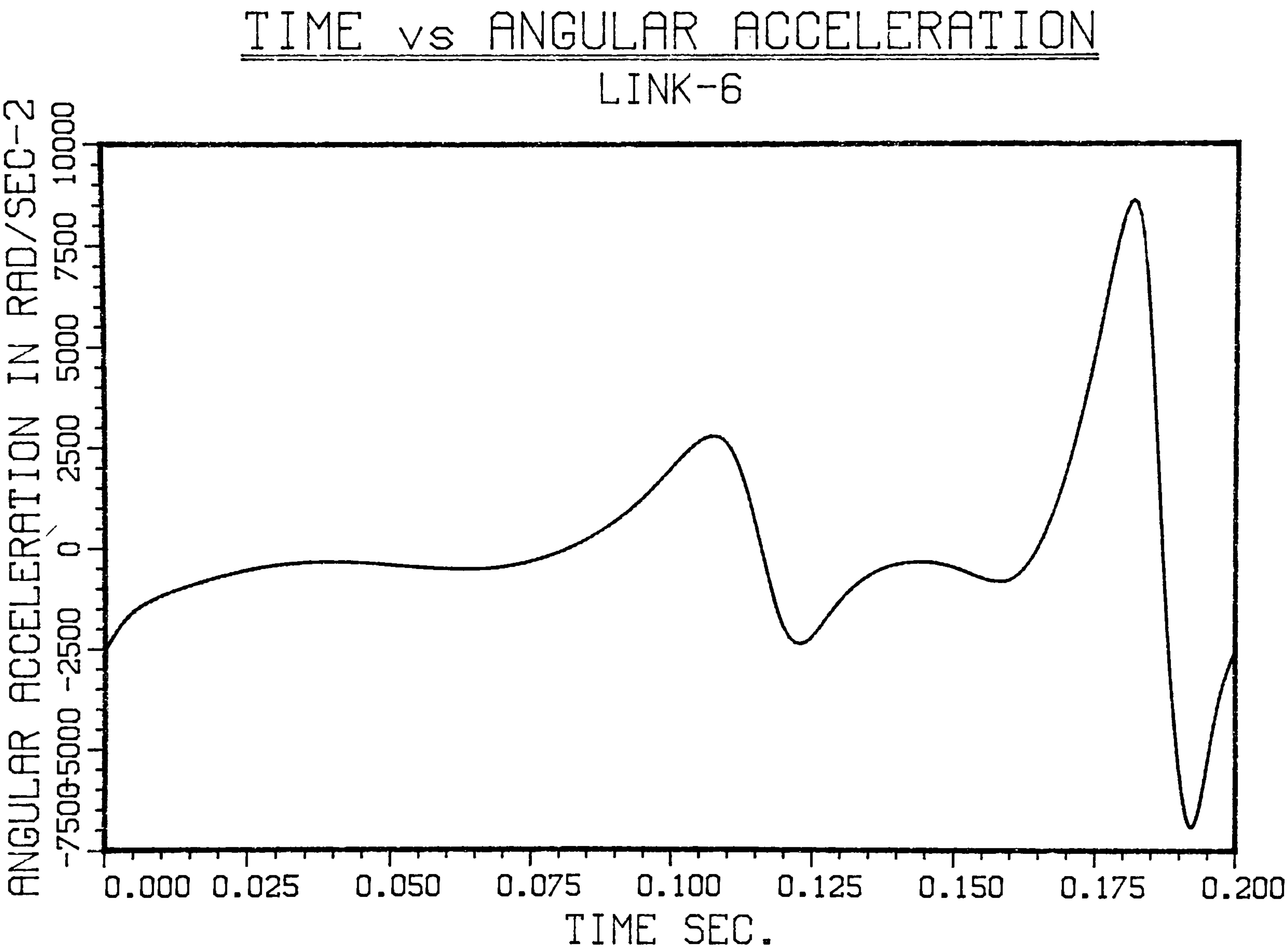

FIG. 14. : ANGULAR ACCELERATION OF LINK 6 (ANALYTICAL).

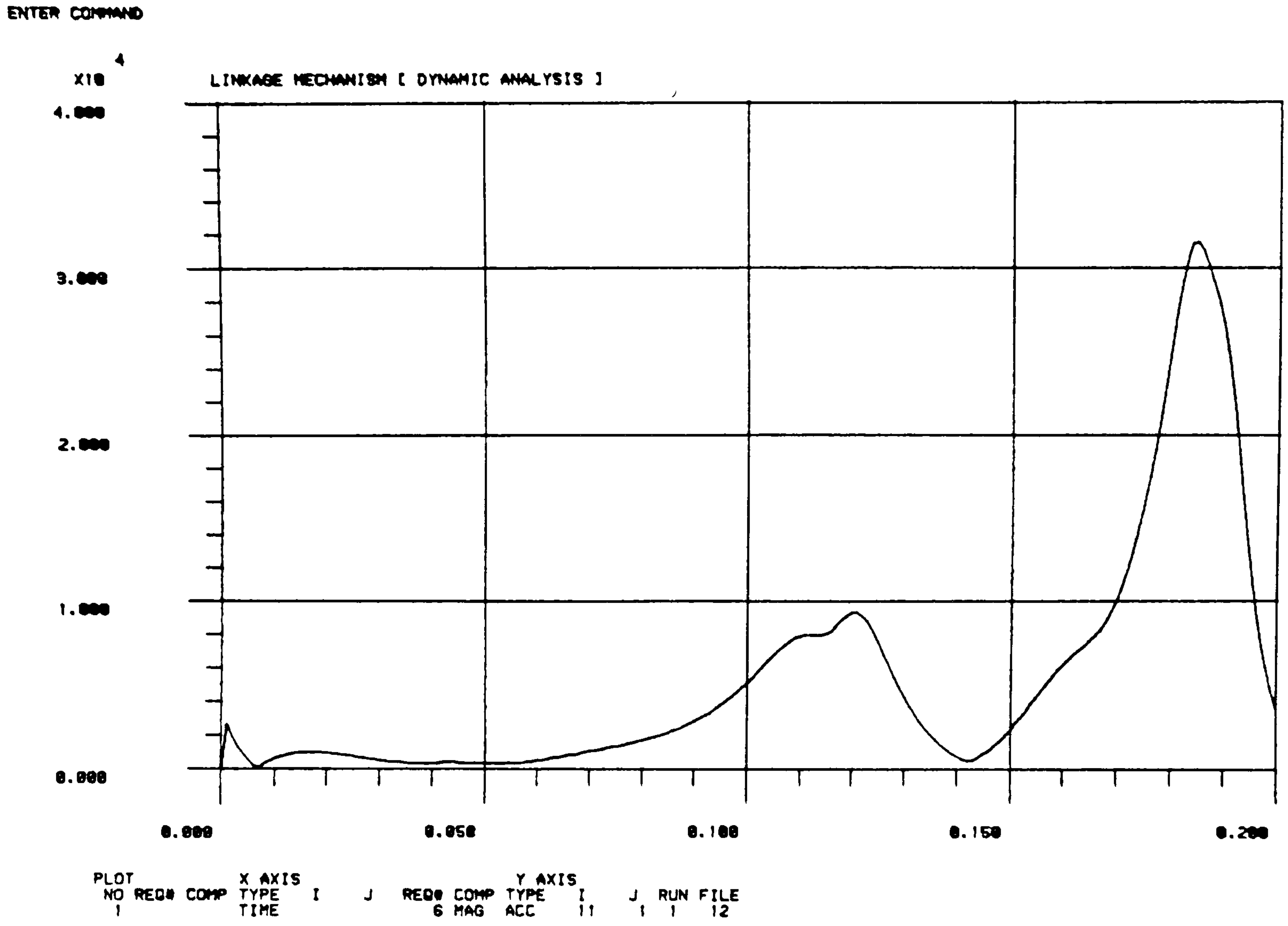

FIG. 15. : LINEAR ACCELERATION OF LINK 7 (DRAM).

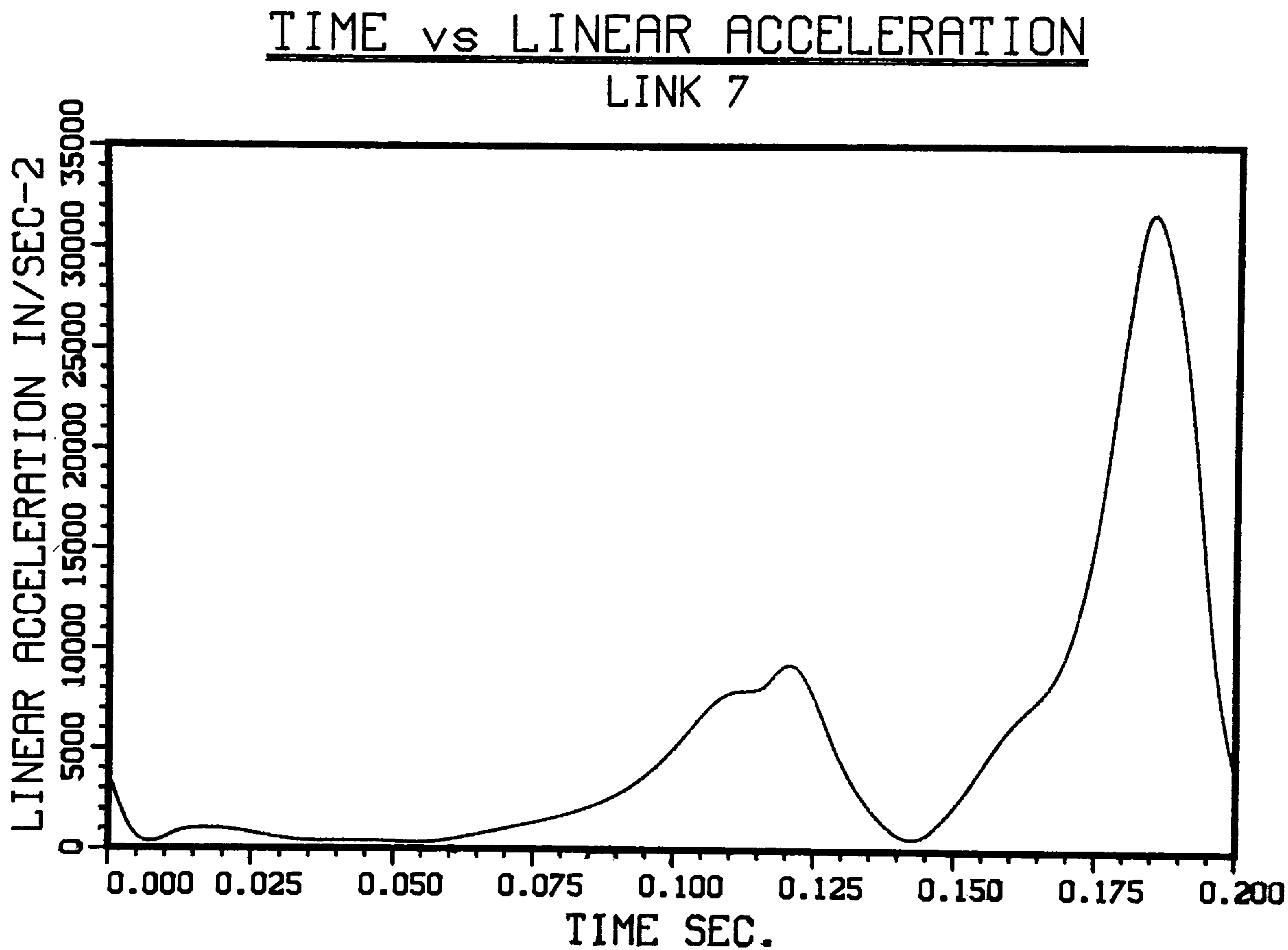

FIG. 16. : LINEAR ACCELERATION OF LINK 7 (ANALYTICAL).

graph does not agree with the plotted numbers of angular displacement of link 6 on the y axis of the analytical graph. The tabulated numerical output from both solutions show a close match (see page 59 and the T6 column on page 71 of appendix B). It appears that there is a software problem in DRAM's plotting routine. A careful observation shows that there is a short delay in plotting the first value on the DRAM graph. DRAM draws a straight line from the origin to this delayed point. This is true for all plots of DRAM. The angular displacement of link 7 in figure 7 is consistent with the angular displacement of link 7 in figure 8. In figure 9 the angular velocity of link 6 is consistent with the angular velocity of link 6 in figure 10. The linear velocity values of the plot of link 7 in figure 11 and figure 12 are consisten except near the 0.15 sec. time area in the DRAM graph. The tabular values of the linear velocity in this region are actually negative. In the DRAM graph the negative values are not plotted on the y axis. As a result, the DRAM graph is inconsistent near the 0.15 sec. region. Again it appears that there is a software problem here in DRAM's plotting routine. Figure 13 and figure 14 show the agreement of the angular acceleration results of link 6. Finally, there is also an agreement of the linear acceleration results of link 7 in figure 15 and figure 16.

The following equations have been used to convert the angular velocity and acceleration into the linear velocity and acceleration respectively:

$$V = R(W) \quad \text{------------------------------} \quad (14)$$

$$A_n = R(W)^2 \quad \text{------------------------------} \quad (15)$$

$$A_t = R(\alpha) \quad \text{------------------------------} \quad (16)$$

$$A_\ell = \sqrt{A_n^2 + A_t^2} \quad \text{------------------------------} \quad (17)$$

where V is the linear velocity, R is the length of the link, W is the angular velocity of the link, A_n is the normal component of acceleration, A_t is the tangential component of acceleration, α is the angular acceleration, and A_ℓ is the linear acceleration.

Kinetic:

A schematic drawing of the linkage mechanism for the kinetic analysis is shown in figure 17. Shown here are the inertia forces and torques associated with each link. Note that the center of gravity of link 3 is taken for simplicity at the point shown. The vitual work method was used to determine the torque input at link 2 necessary to drive the linkage through one complete cycle. The Newtonian method can also used for this torque analysis, but the virtual work method appears to be a simpler approach. The analytical results for the torque show good agreement with DRAM'S torque results. Plots of these torque results can be seen in figure 18 and figure 19.

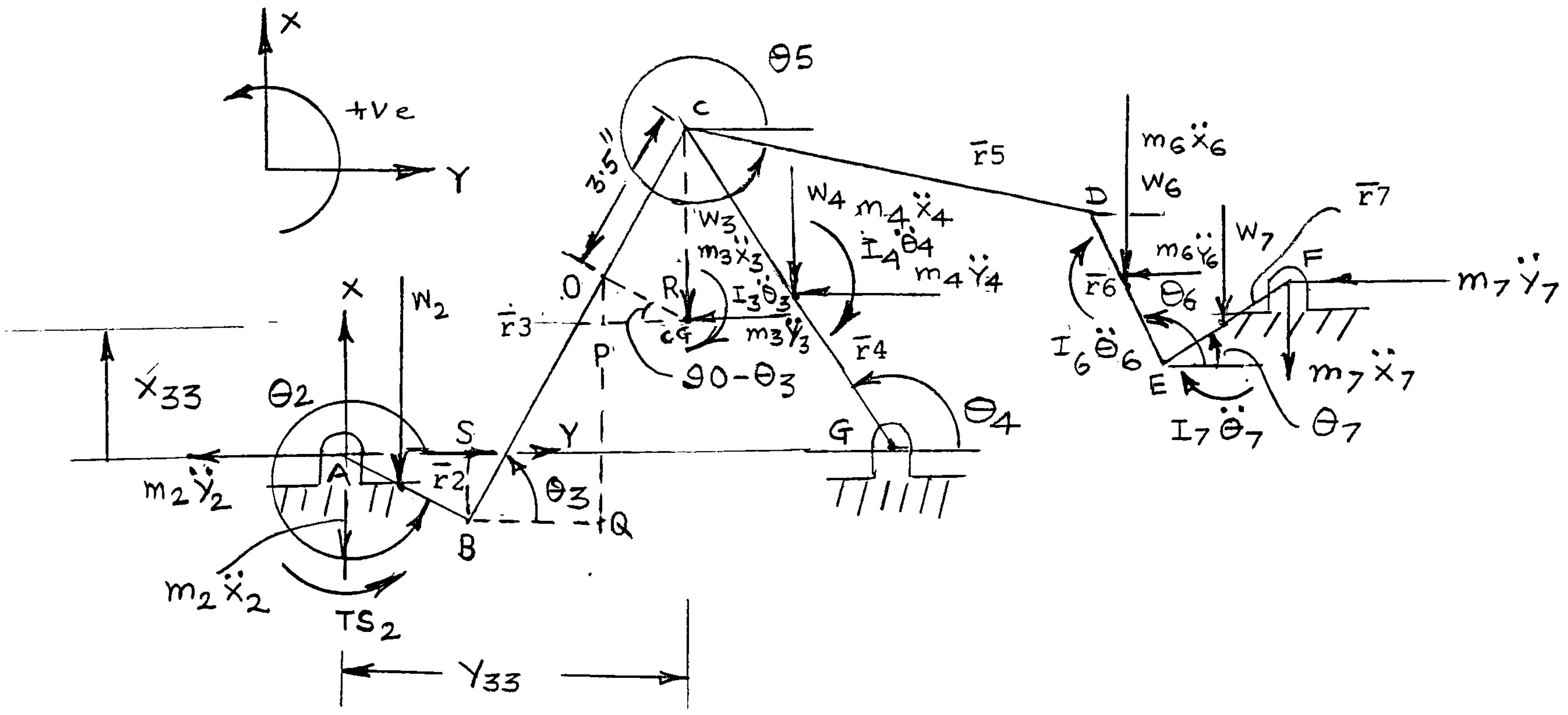

FIG. 17. : LINKAGE MECHANISM WITH INERTIA FORCES AND TORQUES.

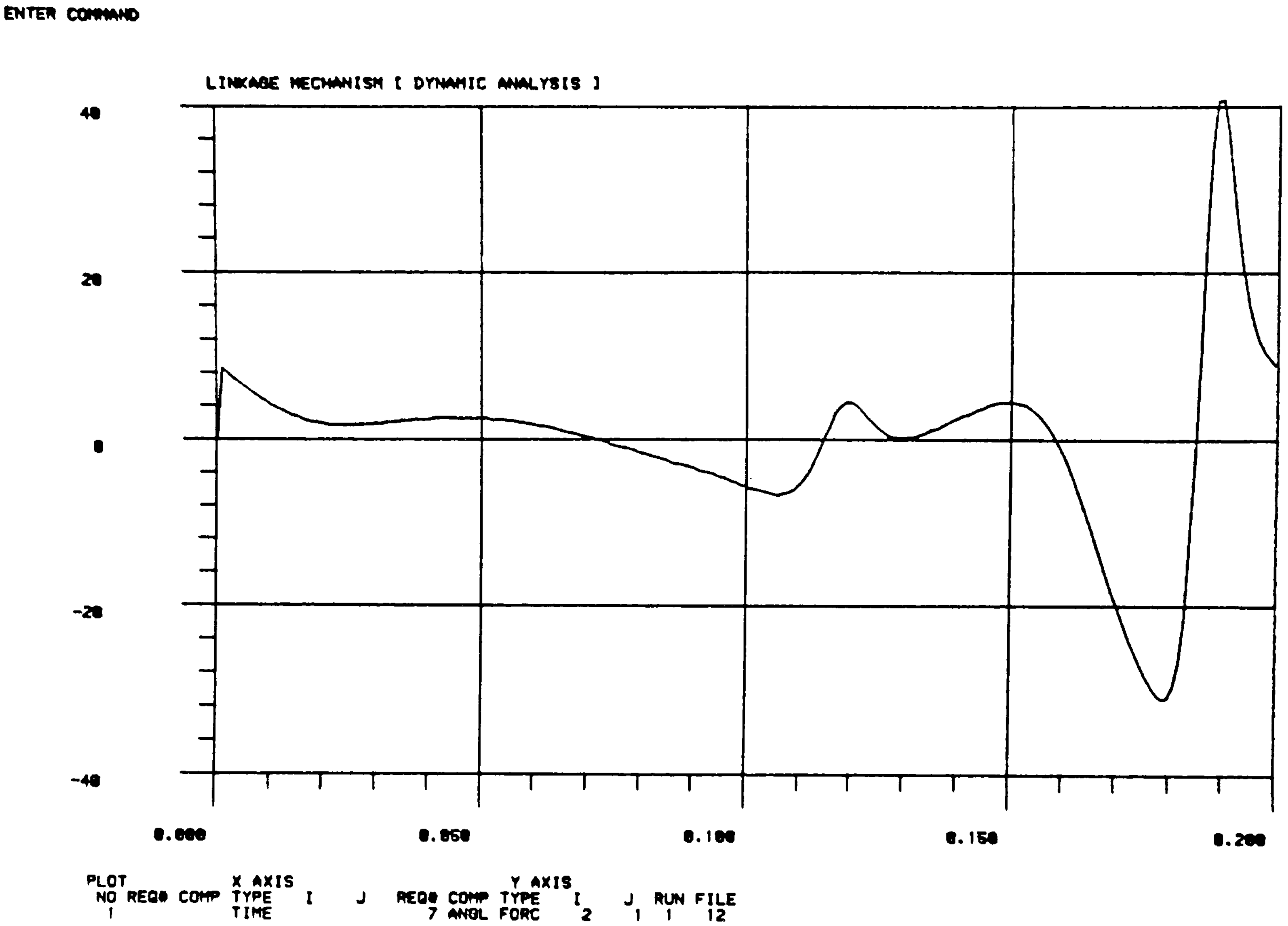

FIG. 18. : TORQUE AT LINK 2 (DRAM).

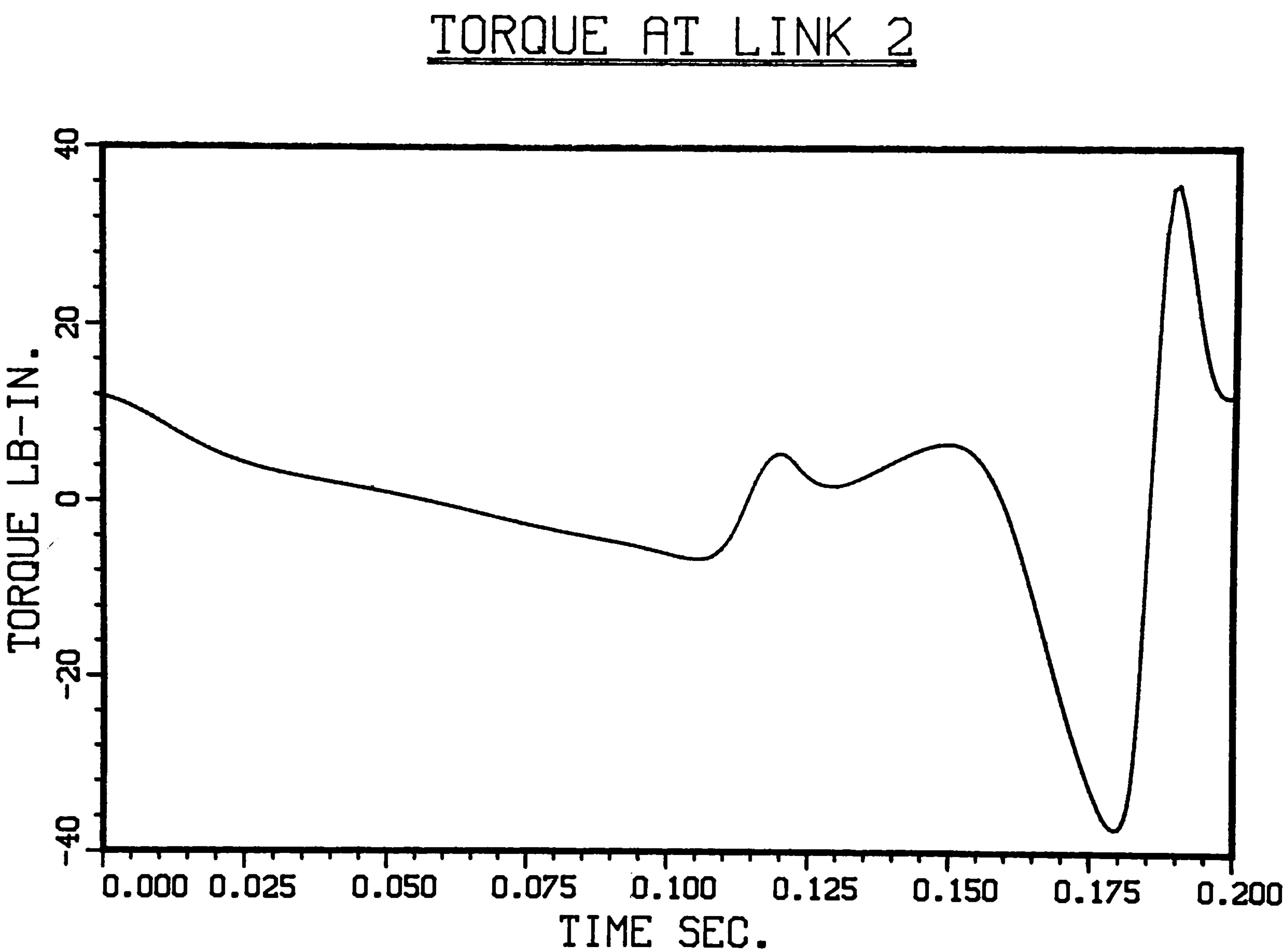

FIG. 19. : TORQUE AT LINK 2 (ANALYTICAL).

VIII. SUMMARY

The DRAM software package has proven its usefulness and effectiveness in the analysis of a complex linkage mechanism. The DRAM postprocessor has also shown its importance in computer-aided-design. In short, it was determined that DRAM is effectively applicable to solve mechanical systems of the linkage type. The major findings of this study are enumerated below:

1. The computer graphics of the linkage mechanism were generated by developing a graphics program. Plotting of the DRAM results was done by using DRAM's plotting commands with the help of the Tektronix terminal. Smoothness of the curves was achieved by increasing the step size in the output statement to 200, although the input data coding shows 50 steps. The step size of 50 is used to abbreviate the number of output values of the results.
2. The obtained values of the displacements, velocities, accelerations and torque by DRAM compare well with the analytical results. The results obtained by DRAM are, therefore, consistent with those of the complex variable method.

A simplified version of the DRAM user manual presents the second part of the study. In this user manual, several examples are presented. The examples are discussed in such a manner that the reader's familarity with DRAM is built up in steps. All input data coding statements of DRAM are simplified and made understandable by referring to the sample examples from time to time. The manual also provides chapters on getting started with DRAM and DRAM graphics on the vax/vms system at the Rochester Institute of Technology. Finally, an important thing included in the manual is a chapter on " how to overcome common mistakes and difficulties which might occur while running DRAM ".

It was found that there are some difficulties in the DRAM software. These difficulties can be encountered as follows:

DRAM does not provide the angular velocity and acceleration if the link is rotating about a fixed point. In such a situation it was necessary to convert the calculated angular velocity, and acceleration by an analytical method into the linear velocity, and acceleration respectively for the comparison of results. It is also noticed during this thesis that there is a DRAM software problem in the plotting routine. DRAM always starts the plot from the origin regardless of the starting value. Some of the plots are not properly labeled on the y axis as well.

IX. REFERENCES

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X. APPENDIX A: ANALYTICAL SOLUTION

Mathematical Derivations:

As shown in fig. 2 the position vectors for loop I can be written as follows.

$$\bar{r}_2 + \bar{r}_3 - \bar{r}_4 = \bar{r}_1$$

or
$$\bar{r}_2 e^{i\theta_2} + \bar{r}_3 e^{i\theta_3} - \bar{r}_4 e^{i\theta_4} = \bar{r}_1 e^{i\theta_1}$$

$$\bar{r}_2(\cos\theta_2 + i\sin\theta_2) + \bar{r}_3(\cos\theta_3 + i\sin\theta_3) - \bar{r}_4(\cos\theta_4 + i\sin\theta_4) = \bar{r}_1$$

Separating real and imaginary parts we have

$$\bar{r}_2\cos\theta_2 + \bar{r}_3\cos\theta_3 - \bar{r}_4\cos\theta_4 = \bar{r}_1 \quad --- \quad (A-1)$$

$$\bar{r}_2\sin\theta_2 + \bar{r}_3\sin\theta_3 - \bar{r}_4\sin\theta_4 = 0 \quad --- \quad (A-2)$$

Rearranging equations (1) and (2)

$$\bar{r}_3\cos\theta_3 = \bar{r}_1 - \bar{r}_2\cos\theta_2 + \bar{r}_4\cos\theta_4$$

$$\bar{r}_3\sin\theta_3 = -\bar{r}_2\sin\theta_2 + \bar{r}_4\sin\theta_4$$

Let

$$a_1 = \bar{r}_1 - \bar{r}_2\cos\theta_2$$

$$b_1 = -\bar{r}_2\sin\theta_2$$

$$\bar{r}_3\cos\theta_3 = a_1 + \bar{r}_4\cos\theta_4 \quad ------ \quad (A-3)$$

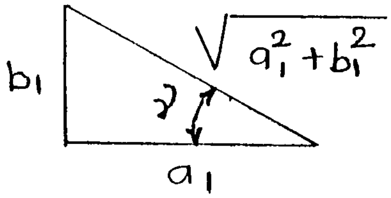
$$\bar{r}_3\sin\theta_3 = b_1 + \bar{r}_4\sin\theta_4 \quad ------ \quad (A-4)$$

Squaring and adding (3) and (4)

$$\bar{r}_3^2 = a_1^2 + b_1^2 + \bar{r}_4^2 + 2a_1\bar{r}_4\cos\theta_4 + 2b_1\bar{r}_4\sin\theta_4$$

$$a_1\cos\theta_4 + b_1\sin\theta_4 = -\left(\frac{a_1^2 + b_1^2 + \bar{r}_4^2 - \bar{r}_3^2}{2\bar{r}_4}\right) \quad --- \quad (A-5)$$

Equation 5 is a transcendental equation in $\theta 4$. To solve for $\theta 4$ use the phase angle method (γ is the phase angle).



$$\sin\gamma = \frac{b_1}{\sqrt{a_1^2+b_1^2}}$$

$$\cos\gamma = \frac{a_1}{\sqrt{a_1^2+b_1^2}}$$

$$\gamma = \tan^{-1}\left[\frac{b_1}{a_1}\right]$$

Now equation (5) becomes

$$\sqrt{a_1^2+b_1^2}\,(\cos\theta_4\cos\gamma + \sin\theta_4\sin\gamma) = -\frac{a_1^2+b_1^2+\bar{r}_4^2-\bar{r}_3^2}{2\bar{r}_4}$$

$$\therefore\ \cos(\theta_4-\gamma) = -\left(\frac{a_1^2+b_1^2+\bar{r}_4^2-\bar{r}_3^2}{2\bar{r}_4\sqrt{a_1^2+b_1^2}}\right)$$

Let us convert the cosine term into the tangent by using

$$\cos\theta = 1/\sqrt{1+\tan^2\theta}$$

$$\therefore\ \frac{1}{\sqrt{1+\tan^2(\theta_4-\gamma)}} = -\left(\frac{a_1^2+b_1^2+\bar{r}_4^2-\bar{r}_3^2}{2\bar{r}_4\sqrt{a_1^2+b_1^2}}\right)$$

Squaring both sides we get

$$\frac{1}{1+\tan^2(\theta_4-\gamma)} = \frac{(-a_1^2-b_1^2-\bar{r}_4^2+\bar{r}_3^2)^2}{(2\bar{r}_4\sqrt{a_1^2+b_1^2})^2}$$

After simplifying we have

$$\theta_4 = \tan^{-1}\left[\frac{\sqrt{4\bar{r}_4^2(a_1^2+b_1^2)-(-a_1^2-b_1^2-\bar{r}_4^2+\bar{r}_3^2)^2}}{(-a_1^2-b_1^2-\bar{r}_4^2+\bar{r}_3^2)}\right]+\gamma$$

Divide equation (2) by equation (1)

$$\frac{\cancel{\bar{r}_3}\sin\theta_3}{\cancel{\bar{r}_3}\cos\theta_3} = \frac{b_1+\bar{r}_4\sin\theta_4}{a_1+\bar{r}_4\cos\theta_4}$$

$$\therefore \tan\theta_3 = \frac{b_1+\bar{r}_4\sin\theta_4}{a_1+\bar{r}_4\cos\theta_4}$$

$$\theta_3 = \tan^{-1}\left[\frac{b_1+\bar{r}_4\sin\theta_4}{a_1+\bar{r}_4\cos\theta_4}\right]$$

Velocity : Differentiate equations (1) and (2). We get

$$\bar{r}_2(-\sin\theta_2)\dot{\theta}_2+\bar{r}_3(-\sin\theta_3)\dot{\theta}_3-\bar{r}_4(-\sin\theta_4)\dot{\theta}_4=0 \quad ---(A-6)$$

$$\bar{r}_2(\cos\theta_2)\dot{\theta}_2+\bar{r}_3(\cos\theta_3)\dot{\theta}_3-\bar{r}_4(\cos\theta_4)\dot{\theta}_4=0 \quad ---(A-7)$$

Rearranging

$$-\bar{r}_3\sin\theta_3\dot{\theta}_3+\bar{r}_4\sin\theta_4\dot{\theta}_4=\bar{r}_2\sin\theta_2\dot{\theta}_2$$

$$\bar{r}_3\cos\theta_3\dot{\theta}_3-\bar{r}_4\cos\theta_4\dot{\theta}_4=-\bar{r}_2\cos\theta_2\dot{\theta}_2$$

$$\therefore \dot{\theta}_3 = \frac{\begin{vmatrix}\bar{r}_2\sin\theta_2\dot{\theta}_2 & \bar{r}_4\sin\theta_4\\ -\bar{r}_2\cos\theta_2\dot{\theta}_2 & -\bar{r}_4\cos\theta_4\end{vmatrix}}{\begin{vmatrix}-\bar{r}_3\sin\theta_3 & \bar{r}_4\sin\theta_4\\ \bar{r}_3\cos\theta_3 & -\bar{r}_4\cos\theta_4\end{vmatrix}}$$

$$= \frac{-\bar{r}_2}{\bar{r}_3}\dot{\theta}_2\,\frac{\sin(\theta_2-\theta_4)}{\sin(\theta_3-\theta_4)}$$

Similarly,

$$\dot{\theta}_4 = \frac{\begin{vmatrix} -\bar{r}_3 \sin\theta_3 & \bar{r}_2 \sin\theta_2 \dot{\theta}_2 \\ \bar{r}_3 \cos\theta_3 & -\bar{r}_2 \cos\theta_2 \dot{\theta}_2 \end{vmatrix}}{\begin{vmatrix} -\bar{r}_3 \sin\theta_3 & \bar{r}_4 \sin\theta_4 \\ \bar{r}_3 \cos\theta_3 & -\bar{r}_4 \cos\theta_4 \end{vmatrix}}$$

$$= \frac{\bar{r}_2}{\bar{r}_4} \dot{\theta}_2 \quad \frac{\sin(\theta_3 - \theta_2)}{\sin(\theta_3 - \theta_4)}$$

Acceleration : Differentiate equations (6) and (7). We have

$$\bar{r}_2(-\cos\theta_2)(\dot{\theta}_2)^2 + \bar{r}_2 \cancelto{0}{(-\sin\theta_2)} \ddot{\theta}_2 + \bar{r}_3(-\cos\theta_3)(\dot{\theta}_3)^2$$
$$+ \bar{r}_3(-\sin\theta_3)\ddot{\theta}_3 - \bar{r}_4(-\cos\theta_4)(\dot{\theta}_4)^2 - \bar{r}_4(-\sin\theta_4)\ddot{\theta}_4 = 0$$
$$\text{----} (A\text{-}8)$$

$$\bar{r}_2(-\sin\theta_2)(\dot{\theta}_2)^2 + \bar{r}_2 \cancelto{0}{(\cos\theta_2)} \ddot{\theta}_2 + \bar{r}_3(-\sin\theta_3)(\dot{\theta}_3)^2$$
$$+ \bar{r}_3(\cos\theta_3)\ddot{\theta}_3 - \bar{r}_4(-\sin\theta_4)(\dot{\theta}_4)^2 - \bar{r}_4(\cos\theta_4)\ddot{\theta}_4 = 0$$
$$\text{----} (A\text{-}9)$$

Rearranging

$$-\bar{r}_3 \sin\theta_3 \ddot{\theta}_3 + \bar{r}_4 \sin\theta_4 \ddot{\theta}_4 =$$
$$\bar{r}_2 \cos\theta_2 (\dot{\theta}_2)^2 + \bar{r}_3 (\cos\theta_3)(\dot{\theta}_3)^2 - \bar{r}_4 \cos\theta_4 (\dot{\theta}_4)^2 = I$$

$$\bar{r}_3 \cos\theta_3 \ddot{\theta}_3 - \bar{r}_4 \cos\theta_4 \ddot{\theta}_4 =$$
$$\bar{r}_2 \sin\theta_2 (\dot{\theta}_2)^2 + \bar{r}_3 \sin\theta_3 (\dot{\theta}_3)^2 - \bar{r}_4 \sin\theta_4 (\dot{\theta}_4)^2 = J$$

$$\ddot{\theta}_3 = \frac{\begin{vmatrix} I & \bar{r}_4 \sin\theta_4 \\ J & -\bar{r}_4 \cos\theta_4 \end{vmatrix}}{\begin{vmatrix} -\bar{r}_3 \sin\theta_3 & \bar{r}_4 \sin\theta_4 \\ \bar{r}_3 \cos\theta_3 & -\bar{r}_4 \cos\theta_4 \end{vmatrix}} = \frac{N}{D}$$

$$N = -\bar{r}_2\bar{r}_4(\dot{\theta}_2)^2\left[\cos\theta_2\cos\theta_4 + \sin\theta_2\sin\theta_4\right] \\ -\bar{r}_3\bar{r}_4(\dot{\theta}_3)^2\left[\cos\theta_3\cos\theta_4 + \sin\theta_3\sin\theta_4\right] + \bar{r}_4^2(\dot{\theta}_4)^2$$

$$D = \bar{r}_3\bar{r}_4\sin\theta_3\cos\theta_4 - \bar{r}_3\bar{r}_4\cos\theta_3\sin\theta_4 \\ = \bar{r}_3\bar{r}_4\sin(\theta_3-\theta_4)$$

$$\ddot{\theta}_3 = \frac{-\bar{r}_2(\dot{\theta}_2)^2\cos(\theta_2-\theta_4) - \bar{r}_3(\dot{\theta}_3)^2\cos(\theta_3-\theta_4) + \bar{r}_4(\dot{\theta}_4)^2}{\bar{r}_3\sin(\theta_3-\theta_4)}$$

Similarly,

$$\ddot{\theta}_4 = \frac{\begin{vmatrix} -\bar{r}_3 \sin\theta_3 & I \\ \bar{r}_3 \cos\theta_3 & J \end{vmatrix}}{\begin{vmatrix} -\bar{r}_3 \sin\theta_3 & \bar{r}_4 \sin\theta_4 \\ \bar{r}_3 \cos\theta_3 & -\bar{r}_4 \cos\theta_4 \end{vmatrix}} = \frac{N}{D}$$

$$N = -\bar{r}_2\bar{r}_3(\dot{\theta}_2)^2(\cos\theta_2\cos\theta_3 + \sin\theta_2\sin\theta_3) \\ -\bar{r}_3^2(\dot{\theta}_3)^2 + \bar{r}_3\bar{r}_4(\dot{\theta}_4)^2(\cos\theta_3\cos\theta_4 + \sin\theta_3\sin\theta_4)$$

$$\ddot{\theta}_4 = \frac{-\bar{r}_2(\dot{\theta}_2)^2\cos(\theta_2-\theta_3) - \bar{r}_3(\dot{\theta}_3)^2 + \bar{r}_4(\dot{\theta}_4)^2\cos(\theta_3-\theta_4)}{\bar{r}_4\sin(\theta_3-\theta_4)}$$

Now the position vectors for loop II can be written as follows.

$$\bar{r}_4 + \bar{r}_5 + \bar{r}_6 + \bar{r}_7 = \bar{r}_8$$

The above equation can be written in the complex form as

$$\bar{r}_4\cos\theta_4 + \bar{r}_5\cos\theta_5 + \bar{r}_6\cos\theta_6 + \bar{r}_7\cos\theta_7 = \bar{r}_8\cos\psi \quad \text{---(A-10)}$$

$$\bar{r}_4\sin\theta_4 + \bar{r}_5\sin\theta_5 + \bar{r}_6\sin\theta_6 + \bar{r}_7\sin\theta_7 = \bar{r}_8\sin\psi \quad \text{---(A-11)}$$

Rearranging

$$\bar{r}_6\cos\theta_6 = \bar{r}_8\cos\psi - \bar{r}_4\cos\theta_4 - \bar{r}_5\cos\theta_5 - \bar{r}_7\cos\theta_7$$

$$\bar{r}_6\sin\theta_6 = \bar{r}_8\sin\psi - \bar{r}_4\sin\theta_4 - \bar{r}_5\sin\theta_5 - \bar{r}_7\sin\theta_7$$

Let

$$a_2 = \bar{r}_8\cos\psi - \bar{r}_4\cos\theta_4 - \bar{r}_5\cos\theta_5$$

$$b_2 = \bar{r}_8\sin\psi - \bar{r}_4\sin\theta_4 - \bar{r}_5\sin\theta_5$$

$$\bar{r}_6\cos\theta_6 = a_2 - \bar{r}_7\cos\theta_7 \quad \text{------ (A-12)}$$

$$\bar{r}_6\sin\theta_6 = b_2 - \bar{r}_7\sin\theta_7 \quad \text{------ (A-13)}$$

Squaring and adding equations (12) and (13) we have

$$\bar{r}_6^2 = a_2^2 + b_2^2 + \bar{r}_7^2 - 2a_2\bar{r}_7\cos\theta_7 - 2b_2\bar{r}_7\sin\theta_7$$

$$a_2\cos\theta_7 + b_2\sin\theta_7 = \frac{-\bar{r}_6^2 + a_2^2 + b_2^2 + \bar{r}_7^2}{2\bar{r}_7}$$

By using the phase angle method we get

$$\sqrt{a_2^2+b_2^2}\,(\cos\theta_7\cos\gamma_1+\sin\theta_7\sin\gamma_1) = \frac{-\bar{r}_6^2-a_2^2-b_2^2-\bar{r}_7^2}{2\bar{r}_7}$$

where

$$\cos\gamma_1 = \frac{a_2}{\sqrt{a_2^2+b_2^2}}\ ;\ \sin\gamma_1 = \frac{b_2}{\sqrt{a_2^2+b_2^2}}\ ;\ \tan\gamma_1 = \frac{b_2}{b_1}$$

$$\therefore\ \gamma_1 = \tan^{-1}\left[\frac{b_2}{a_2}\right]$$

$$\therefore\ \cos(\theta_7-\gamma_1) = \frac{-\bar{r}_6^2+a_2^2+b_2^2+\bar{r}_7^2}{2\bar{r}_7\sqrt{a_2^2+b_2^2}}$$

$$\frac{1}{\sqrt{1+\tan^2(\theta_7-\gamma_1)}} = \frac{-\bar{r}_6^2+a_2^2+b_2^2+\bar{r}_7^2}{2\bar{r}_7\sqrt{a_2^2+b_2^2}}$$

Squaring both sides we have

$$\frac{1}{1+\tan^2(\theta_7-\gamma_1)} = \frac{(-\bar{r}_6^2+a_2^2+b_2^2+\bar{r}_7^2)^2}{(2\bar{r}_7\sqrt{a_2^2+b_2^2})^2}$$

After simplifying we get

$$\theta_7 = \tan^{-1}\left[\frac{\sqrt{(2\bar{r}_7\sqrt{a_2^2+b_2^2})^2-(a_2^2+b_2^2+\bar{r}_7^2-\bar{r}_6^2)^2}}{(a_2^2+b_2^2+\bar{r}_7^2-\bar{r}_6^2)}\right]+\gamma_1$$

Divide equation (13) by equation (12).

$$\tan\theta_6 = \frac{b_2 - \bar{r}_7 \sin\theta_7}{a_2 - \bar{r}_7 \cos\theta_7}$$

$$\therefore \quad \theta_6 = \tan^{-1}\left[\frac{b_2 - \bar{r}_7 \sin\theta_7}{a_2 - \bar{r}_7 \cos\theta_7}\right]$$

Velocity : Differentiate equations (10) and (11). We get

$$\bar{r}_4(-\sin\theta_4)(\dot{\theta}_4) + \bar{r}_5(-\sin\theta_5)\dot{\theta}_5 + \bar{r}_6(-\sin\theta_6)(\dot{\theta}_6) + \bar{r}_7(-\sin\theta_7)(\dot{\theta}_7) = 0 \quad \text{-----} \quad (A\text{-}14)$$

$$\bar{r}_4\cos\theta_4(\dot{\theta}_4) + \bar{r}_5\cos\theta_5(\dot{\theta}_5) + \bar{r}_6\cos\theta_6(\dot{\theta}_6) + \bar{r}_7\cos\theta_7(\dot{\theta}_7) = 0 \quad \text{------} \quad (A\text{-}15)$$

$$\theta_5 = 180 + \theta_3 + 120$$
$$= 300 + \theta_3$$
$$\dot{\theta}_5 = \dot{\theta}_3$$

Rearranging equations (14) and (15) we get

$$-\bar{r}_6\sin\theta_6(\dot{\theta}_6) - \bar{r}_7\sin\theta_7(\dot{\theta}_7) = +\bar{r}_4\sin\theta_4(\dot{\theta}_4) + \bar{r}_5\sin\theta_5(\dot{\theta}_3) = A$$

$$\bar{r}_6\cos\theta_6(\dot{\theta}_6) + \bar{r}_7\cos\theta_7(\dot{\theta}_7) = -\bar{r}_4\cos\theta_4(\dot{\theta}_4) - \bar{r}_5\cos\theta_5(\dot{\theta}_3) = B$$

$$\therefore \dot{\theta}_6 = \frac{\begin{vmatrix} A & -\bar{r}_7\sin\theta_7 \\ B & \bar{r}_7\cos\theta_7 \end{vmatrix}}{\begin{vmatrix} -\bar{r}_6\sin\theta_6 & -\bar{r}_7\sin\theta_7 \\ \bar{r}_6\cos\theta_6 & \bar{r}_7\cos\theta_7 \end{vmatrix}}$$

$$\dot{\theta}_6 = \frac{A\bar{r}_7 \cos\theta_7 + B\bar{r}_7 \sin\theta_7}{-\bar{r}_6 \bar{r}_7 \sin(\theta_6-\theta_7)}$$

Similarly,

$$\dot{\theta}_7 = \frac{\begin{vmatrix} -\bar{r}_6 \sin\theta_6 & A \\ \bar{r}_6 \cos\theta_6 & B \end{vmatrix}}{\begin{vmatrix} -\bar{r}_6 \sin\theta_6 & -\bar{r}_7 \sin\theta_7 \\ \bar{r}_6 \cos\theta_6 & \bar{r}_7 \cos\theta_7 \end{vmatrix}}$$

$$= \frac{-B\bar{r}_6 \sin\theta_6 - A\bar{r}_6 \cos\theta_6}{-\bar{r}_6 \bar{r}_7 \sin(\theta_6-\theta_7)}$$

Acceleration : Differentiate equations (14) and (15). We have

$$\bar{r}_4(-\cos\theta_4)(\dot{\theta}_4)^2 + \bar{r}_4(-\sin\theta_4)\ddot{\theta}_4 + \bar{r}_5(-\cos\theta_5)(\dot{\theta}_5)^2 + \bar{r}_5(-\sin\theta_5)(\ddot{\theta}_5) + \bar{r}_6(-\cos\theta_6)(\dot{\theta}_6)^2 + \bar{r}_6(-\sin\theta_6)\ddot{\theta}_6 + \bar{r}_7(-\cos\theta_7)(\dot{\theta}_7)^2 + \bar{r}_7(-\sin\theta_7)\ddot{\theta}_7 = 0 \quad ----(A\text{-}16)$$

$$\bar{r}_4(-\sin\theta_4)(\dot{\theta}_4)^2 + \bar{r}_4(\cos\theta_4)\ddot{\theta}_4 + \bar{r}_5(-\sin\theta_5)(\dot{\theta}_5)^2 + \bar{r}_5(\cos\theta_5)\ddot{\theta}_5 + \bar{r}_6(-\sin\theta_6)(\dot{\theta}_6)^2 + \bar{r}_6(\cos\theta_6)\ddot{\theta}_6 + \bar{r}_7(-\sin\theta_7)(\dot{\theta}_7)^2 + \bar{r}_7(\cos\theta_7)\ddot{\theta}_7 = 0 \quad -----(A\text{-}17)$$

Rearranging

$$\bar{r}_6(-\sin\theta_6)\ddot{\theta}_6 + \bar{r}_7(-\sin\theta_7)\ddot{\theta}_7$$
$$= \bar{r}_4(-\cos\theta_4)(\dot{\theta}_4)^2 + \bar{r}_4(-\sin\theta_4)\ddot{\theta}_4 + \bar{r}_5(-\cos\theta_5)(\dot{\theta}_5)^2 + \bar{r}_5(-\sin\theta_5)(\ddot{\theta}_5) + \bar{r}_6(-\cos\theta_6)(\dot{\theta}_6)^2 + \bar{r}_7(-\cos\theta_7)(\dot{\theta}_7)^2 = P$$

$$\bar{r}_6 ((\cos\theta_6)\ddot{\theta}_6 + \bar{r}_7 ((\cos\theta_7)\ddot{\theta}_7$$
$$= \bar{r}_4(-\sin\theta_4)(\dot{\theta}_4)^2 + \bar{r}_4((\cos\theta_4)\ddot{\theta}_4 + \bar{r}_5(-\sin\theta_5)(\dot{\theta}_5)^2$$
$$+ \bar{r}_5((\cos\theta_5)\ddot{\theta}_5 + \bar{r}_6(-\sin\theta_6)(\dot{\theta}_6)^2 + \bar{r}_7(-\sin\theta_7)(\dot{\theta}_7)^2 = Q$$

$$\dot{\theta}_5 = \dot{\theta}_3 \quad ; \quad \ddot{\theta}_5 = \ddot{\theta}_3$$

$$\ddot{\theta}_6 = \frac{\begin{vmatrix} P & \bar{r}_7\sin\theta_7 \\ Q & -\bar{r}_7\cos\theta_7 \end{vmatrix}}{\begin{vmatrix} \bar{r}_6\sin\theta_6 & \bar{r}_7\sin\theta_7 \\ -\bar{r}_6\cos\theta_6 & -\bar{r}_7\cos\theta_7 \end{vmatrix}}$$

$$= \frac{-P\bar{r}_7\cos\theta_7 - Q\bar{r}_7\sin\theta_7}{-\bar{r}_6\bar{r}_7\sin(\theta_6-\theta_7)}$$

Similarly,

$$\ddot{\theta}_7 = \frac{\begin{vmatrix} \bar{r}_6\sin\theta_6 & P \\ -\bar{r}_6\cos\theta_6 & Q \end{vmatrix}}{\begin{vmatrix} \bar{r}_6\sin\theta_6 & \bar{r}_7\sin\theta_7 \\ -\bar{r}_6\cos\theta_6 & -\bar{r}_7\cos\theta_7 \end{vmatrix}}$$

$$= \frac{Q\bar{r}_6\sin\theta_6 + Q\bar{r}_6\cos\theta_6}{-\bar{r}_6\bar{r}_7\sin(\theta_6-\theta_7}$$

Torque :

The center of mass of each link is shown in figure 17. The displacement, velocity, and acceleration of each link are calculated simultaneously in the following mathematical expressions.

Hence for each link we can write (Refer to figure 17) :

Link 3 :

$$AS = \bar{r}_2 \cos\theta_2$$

$$\dot{AS} = \bar{r}_2(-\sin\theta_2)\dot{\theta}_2$$

$$\ddot{AS} = \bar{r}_2[(-\cos\theta_2)(\dot{\theta}_2)^2 + \cancel{(-\sin\theta_2)}\ddot{\theta}_2]$$

$$BQ = 7.3\cos\theta_3$$

$$\dot{BQ} = 7.3(-\sin\theta_3)\dot{\theta}_3$$

$$\ddot{BQ} = 7.3[(-\cos\theta_3)(\dot{\theta}_3)^2 + (-\sin\theta_3)\ddot{\theta}_3]$$

$$PR = 2.6\cos(90-\theta_3) = 2.6\sin\theta_3$$

$$\dot{PR} = 2.6\cos\theta_3(\dot{\theta}_3)$$

$$\ddot{PR} = 2.6[(-\sin\theta_3)(\dot{\theta}_3)^2 + \cos\theta_3(\ddot{\theta}_3)]$$

$Y_{33} = AS + BQ + PR$ (Distance) ---- (A-18)

$Y_3 = \dot{AS} + \dot{BQ} + \dot{PR} = \dot{Y}_3$ (Velocity) ----- (A-19)

$YY_3 = \ddot{AS} + \ddot{BQ} + \ddot{PR} = \ddot{Y}_3$ (Acceleration) ---- (A-20)

$$BS = \bar{r}_2\sin\theta_2$$

$$\dot{BS} = \bar{r}_2\cos\theta_2\dot{\theta}_2$$

$$\ddot{BS} = \bar{r}_2 \left[(-\sin\theta_2)\dot{\theta}_2^2 + \cancelto{0}{\cos\theta_2}\,\ddot{\theta}_2 \right]$$

$$OQ = 7.3 \sin\theta_3$$

$$\dot{OQ} = 7.3 \cos\theta_3 \, \dot{\theta}_3$$

$$\ddot{OQ} = 7.3 \left[(-\sin\theta_3)(\dot{\theta}_3)^2 + \cos\theta_3 (\ddot{\theta}_3) \right]$$

$$OP = 2.6 \sin(90 - \theta_3) = 2.6 \cos\theta_3$$

$$\dot{OP} = 2.6 (-\sin\theta_3)\dot{\theta}_3$$

$$\ddot{OP} = 2.6 \left[(-\cos\theta_3)(\dot{\theta}_3)^2 + (-\sin\theta_3)\ddot{\theta}_3 \right]$$

$$X_{33} = BS + OQ - OP \quad \text{(Distance)} \quad \text{----(A-21)}$$

$$X_3 = \dot{BS} + \dot{OQ} - \dot{OP} = \dot{x}_3 \quad \text{(Velocity)} \quad \text{----(A-22)}$$

$$XX_3 = \ddot{BS} + \ddot{OQ} - \ddot{OP} = \ddot{x}_3 \quad \text{(Acceleration)} \quad \text{----(A-23)}$$

Link 2 :

$$Y_2 = \frac{\bar{r}_2}{2} \cos\theta_2 \quad \text{-------- (A-24)}$$

$$\dot{Y}_2 = \frac{\bar{r}_2}{2} (-\sin\theta_2)\dot{\theta}_2 \quad \text{-------- (A-25)}$$

$$\ddot{Y}_2 = \frac{\bar{r}_2}{2} \left[(-\cos\theta_2)(\dot{\theta}_2)^2 + (-\cancel{\sin\theta_2})\ddot{\theta}_2 \right] \quad \text{----(A-26)}$$

$$X_2 = \frac{\bar{r}_2}{2} \sin\theta_2 \quad \text{-------- (A-27)}$$

$$\dot{X}_2 = \frac{\bar{r}_2}{2} (\cos\theta_2)\dot{\theta}_2 \quad \text{-------- (A-28)}$$

$$\ddot{X}_2 = \frac{\bar{r}_2}{2} \left[(-\sin\theta_2)(\dot{\theta}_2)^2 + \cancel{\cos\theta_2}\,\ddot{\theta}_2 \right] \quad \text{---(A-29)}$$

```
      RETURN
      END
```

KEYWORD DEFINITIONS:

<u>TIME:</u>

Simulation time.

<u>PAR:</u>

Ten parameters.

<u>NGEN:</u>

Identification number of the generator (same as the ID number of the generator). The NGEN can be used to branch to the appropriate section of the subroutine when more than 1 generator is used in the system.

<u>X:</u>

Is the displacement.

<u>DX:</u>

Is the velocity.

<u>D2X:</u>

Is the acceleration.

<u>For Example:</u>

Refer to the Mechanical Dynamics Inc's user guide (page 74). Also refer example 7.8 of this manual.

XI. APPENDIX B: PROGRAMS AND OUTPUTS

LINKAGE MECHANISM [DYNAMIC ANALYSIS]

```
PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/15,POINT,PART=1,X=8.7,Y=0
MARKER/14,POINT,PART=1,X=15.5,Y=4.0

PART/2,MASS=0.15,CM=3,INERTIA=0.3645,ANGLE=315
PART/2,DEGDANGLE=-1800
MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/3,GMARKER,PART=2,X=1.35,Y=0,ANGLE=0
MARKER/4,POINT,PART=2,X=2.7,Y=0

PART/3,MASS=0.3,CM=19,INERTIA=9.4090,ANGLE=233
MARKER/6,POINT,PART=3,X=0,Y=0
MARKER/5,GMARKER,PART=3,X=10.8,Y=0,ANGLE=0
MARKER/7,POINT,PART=3,X=-3.5,Y=6.0621778
MARKER/19,GMARKER,PART=3,X=3.5,Y=2.6,ANGLE=0

PART/4,MASS=0.25,CM=17,INERTIA=3.8533,ANGLE=93
MARKER/16,GMARKER,PART=4,X=0,Y=0,ANGLE=0
MARKER/17,POINT,PART=4,X=3.4,Y=0
MARKER/18,GMARKER,PART=4,X=6.8,Y=0,ANGLE=0

PART/6,MASS=0.12,CM=9,INERTIA=0.2784,ANGLE=65
MARKER/10,POINT,PART=6,X=0,Y=0
MARKER/9,GMARKER,PART=6,X=1.3,Y=0,ANGLE=0
MARKER/8,POINT,PART=6,X=2.6,Y=0

PART/7,MASS=0.1,CM=12,INERTIA=0.07186,ANGLE=193
MARKER/13,GMARKER,PART=7,X=0,Y=0,ANGLE=0
MARKER/12,POINT,PART=7,X=0.7,Y=0
MARKER/11,POINT,PART=7,X=1.4,Y=0


ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=6,J=18
ROTATION/4,I=7,J=8
ROTATION/5,I=10,J=11
ROTATION/6,I=14,J=13
ROTATION/7,I=15,J=16


GENERATOR/1,ROTATIONAL,ON=2,CONSTVEL,DEGPAR=-1800,PAR=315.0D

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.2,STEPS=50,SAVEINT,GRSAVE,NOPLOT

REQUEST/1,DISPLACEMENT,I=9,J=1
REQUEST/2,DISPLACEMENT,I=12,J=14

REQUEST/3,VELOCITY,I=9,J=1
REQUEST/4,VELOCITY,I=11,J=1

REQUEST/5,ACCELERATION,I=9,J=1
REQUEST/6,ACCELERATION,I=11,J=1
```

```
REQUEST/7,FORCE,I=2,J=1
```

GRAPHICS

```
GRAPHICS/1,OUTLINE=2,4

GRAPHICS/2,OUTLINE=5,6
GRAPHICS/3,OUTLINE=6,7

GRAPHICS/4,CIRCLE,CM=8,RADIUS=0.1
GRAPHICS/5,OUTLINE=8,10

GRAPHICS/6,CIRCLE,CM=11,RADIUS=0.05
GRAPHICS/7,OUTLINE=13,11

GRAPHICS/8,OUTLINE=16,18
GRAPHICS/9,CIRCLE,CM=19,RADIUS=.2
END
```

```
LINKAGE MECHANISM [ DYNAMIC ANALYSIS ]


-- DEFAULT VALUE (TSM1) -- SYSTEM/TS= 4.0000E-03

SYSTEM HAS    0 DEGREE(S) OF FREEDOM
SYSTEM WILL BE SIMULATED IN KINEMATIC MODE



*---- INPUT DATA LOOP CLOSURE CHECK  ----*
I---------------------------------------I
I ROTATION 1 DISPLACEMENT I   VELOCITY  I
I          I    ERROR     I    ERROR    I
I----------I--------------I-------------I
I        3 I  9.87363D-02 I  8.48230D+01 I
I        4 I  2.16149D-01 I  8.48230D+01 I
I----------I--------------I-------------I


LOOP CLOSURE DISPLACEMENT SOLUTION

CONVERGENCE WITHIN   6.51352D-15 IN  4 ITERATIONS

LOOP CLOSURE VELOCITY SOLUTION


CORRECTED INITIAL CONDITIONS


PART/     1    0.000000000000000D+00 DEG    0.000000000000000D+00 RAD/SEC
PART/     2    3.150000000000000D+02 DEG   -3.141592653589793D+01 RAD/SEC
PART/     3    2.336465358888234D+02 DEG    8.194347775570054D+00 RAD/SEC
PART/     4    6.426010474128745D+01 DEG    5.458131723533457D+01 RAD/SEC
PART/     5    1.935402462335677D+02 DEG    8.920737528789960D+00 RAD/SEC
PART/     6    9.327902568285362D+01 DEG    1.933368376638460D+01 RAD/SEC

KFLAG= 0 ORDER= 0 IFCT=   51 H= 0.40000D-02 ITER=    4


IN THE OUTPUT PHASE  2813 WORDS OF MEMORY WERE REQUIRED
```

LINKAGE MECHANISM [DYNAMIC ANALYSIS]

REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR DISPLACEMENT OF MARKER 9 RELATIVE TO MARKER 1	ANGLE (DEGREES)	MAGNITUDE OF THE ANGULAR DISPLACEMENT (DEGS) OF MARKER 9 RELATIVE TO MARKER 1
0.0000E+00	1.54806E+01	1.82315E+01	6.42601E+01
4.0000E-03	1.52741E+01	1.87227E+01	7.57727E+01
8.0000E-03	1.50745E+01	1.90673E+01	8.57147E+01
1.2000E-02	1.48857E+01	1.92413E+01	9.44739E+01
1.6000E-02	1.47105E+01	1.92462E+01	1.02283E+02
2.0000E-02	1.45507E+01	1.90968E+01	1.09316E+02
2.4000E-02	1.44077E+01	1.88150E+01	1.15721E+02
2.8000E-02	1.42821E+01	1.84268E+01	1.21626E+02
3.2000E-02	1.41743E+01	1.79594E+01	1.27134E+02
3.6000E-02	1.40840E+01	1.74391E+01	1.32317E+02
4.0000E-02	1.40103E+01	1.68895E+01	1.37210E+02
4.4000E-02	1.39525E+01	1.63299E+01	1.41822E+02
4.8000E-02	1.39097E+01	1.57745E+01	1.46132E+02
5.2000E-02	1.38816E+01	1.52328E+01	1.50105E+02
5.6000E-02	1.38682E+01	1.47101E+01	1.53699E+02
6.0000E-02	1.38706E+01	1.42081E+01	1.56874E+02
6.4000E-02	1.38900E+01	1.37269E+01	1.59604E+02
6.8000E-02	1.39285E+01	1.32656E+01	1.61887E+02
7.2000E-02	1.39882E+01	1.28240E+01	1.63756E+02
7.6000E-02	1.40714E+01	1.24034E+01	1.65285E+02
8.0000E-02	1.41801E+01	1.20073E+01	1.66593E+02
8.4000E-02	1.43165E+01	1.16417E+01	1.67853E+02
8.8000E-02	1.44821E+01	1.13162E+01	1.69291E+02
9.2000E-02	1.46780E+01	1.10448E+01	1.71200E+02
9.6000E-02	1.49041E+01	1.08477E+01	1.73947E+02
1.0000E-01	1.51581E+01	1.07527E+01	1.77991E+02
1.0400E-01	1.54327E+01	1.07943E+01	1.83864E+02
1.0800E-01	1.57123E+01	1.10015E+01	1.92070E+02
1.1200E-01	1.59703E+01	1.13643E+01	2.02793E+02
1.1600E-01	1.61796E+01	1.17819E+01	2.15363E+02
1.2000E-01	1.63385E+01	1.20712E+01	2.28039E+02
1.2400E-01	1.64770E+01	1.21075E+01	2.39104E+02
1.2800E-01	1.66207E+01	1.19126E+01	2.48157E+02
1.3200E-01	1.67734E+01	1.15707E+01	2.55720E+02
1.3600E-01	1.69289E+01	1.11552E+01	2.62378E+02
1.4000E-01	1.70806E+01	1.07202E+01	2.68510E+02
1.4400E-01	1.72235E+01	1.03117E+01	2.74312E+02
1.4800E-01	1.73548E+01	9.97605E+00	2.79841E+02
1.5200E-01	1.74731E+01	9.76614E+00	2.85032E+02
1.5600E-01	1.75781E+01	9.74402E+00	2.89723E+02
1.6000E-01	1.76680E+01	9.97829E+00	2.93745E+02
1.6400E-01	1.77339E+01	1.05315E+01	2.97139E+02
1.6800E-01	1.77552E+01	1.14382E+01	3.00428E+02
1.7200E-01	1.76978E+01	1.26825E+01	3.04750E+02
1.7600E-01	1.75184E+01	1.41677E+01	3.11852E+02
1.8000E-01	1.71780E+01	1.56597E+01	3.24049E+02
1.8400E-01	1.66929E+01	1.67312E+01	3.43455E+02
1.8800E-01	1.62208E+01	1.70789E+01	3.68672E+02
1.9200E-01	1.59122E+01	1.72327E+01	3.92389E+02
1.9600E-01	1.56900E+01	1.76730E+01	4.10371E+02
2.0000E-01	1.54806E+01	1.82315E+01	4.24260E+02

LINKAGE MECHANISM [DYNAMIC ANALYSIS]

REQUEST NUMBER 2

TIME	MAGNITUDE OF THE LINEAR DISPLACEMENT OF MARKER 12 RELATIVE TO MARKER 14	ANGLE (DEGREES)
0.0000E+00	7.00000E-01	1.93540E+02
4.0000E-03	7.00000E-01	1.94787E+02
8.0000E-03	7.00000E-01	1.95403E+02
1.2000E-02	7.00000E-01	1.96196E+02
1.6000E-02	7.00000E-01	1.97511E+02
2.0000E-02	7.00000E-01	1.99457E+02
2.4000E-02	7.00000E-01	2.02003E+02
2.8000E-02	7.00000E-01	2.05036E+02
3.2000E-02	7.00000E-01	2.08398E+02
3.6000E-02	7.00000E-01	2.11929E+02
4.0000E-02	7.00000E-01	2.15486E+02
4.4000E-02	7.00000E-01	2.18973E+02
4.8000E-02	7.00000E-01	2.22347E+02
5.2000E-02	7.00000E-01	2.25623E+02
5.6000E-02	7.00000E-01	2.28868E+02
6.0000E-02	7.00000E-01	2.32194E+02
6.4000E-02	7.00000E-01	2.35737E+02
6.8000E-02	7.00000E-01	2.39643E+02
7.2000E-02	7.00000E-01	2.44052E+02
7.6000E-02	7.00000E-01	2.49088E+02
8.0000E-02	7.00000E-01	2.54865E+02
8.4000E-02	7.00000E-01	2.61494E+02
8.8000E-02	7.00000E-01	2.69097E+02
9.2000E-02	7.00000E-01	2.77835E+02
9.6000E-02	7.00000E-01	2.87911E+02
1.0000E-01	7.00000E-01	2.99582E+02
1.0400E-01	7.00000E-01	3.13108E+02
1.0800E-01	7.00000E-01	3.28586E+02
1.1200E-01	7.00000E-01	3.45545E+02
1.1600E-01	7.00000E-01	2.29387E+00
1.2000E-01	7.00000E-01	1.58982E+01
1.2400E-01	7.00000E-01	2.40943E+01
1.2800E-01	7.00000E-01	2.70874E+01
1.3200E-01	7.00000E-01	2.64777E+01
1.3600E-01	7.00000E-01	2.37437E+01
1.4000E-01	7.00000E-01	1.99109E+01
1.4400E-01	7.00000E-01	1.57230E+01
1.4800E-01	7.00000E-01	1.18442E+01
1.5200E-01	7.00000E-01	9.01729E+00
1.5600E-01	7.00000E-01	8.16242E+00
1.6000E-01	7.00000E-01	1.03435E+01
1.6400E-01	7.00000E-01	1.65245E+01
1.6800E-01	7.00000E-01	2.72947E+01
1.7200E-01	7.00000E-01	4.29356E+01
1.7600E-01	7.00000E-01	6.37984E+01
1.8000E-01	7.00000E-01	9.04911E+01
1.8400E-01	7.00000E-01	1.22877E+02
1.8800E-01	7.00000E-01	1.56070E+02
1.9200E-01	7.00000E-01	1.79277E+02
1.9600E-01	7.00000E-01	1.89788E+02
2.0000E-01	7.00000E-01	1.93540E+02

LINKAGE MECHANISM [DYNAMIC ANALYSIS]

REQUEST NUMBER 3

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 9 RELATIVE TO MARKER 1	ANGLE (DEGREES)	MAGNITUDE OF THE ANGULAR VELOCITY (RAD) OF MARKER 9 RELATIVE TO MARKER 1
0.0000E+00	6.37856E+01	1.62977E+02	5.45813E+01
4.0000E-03	5.83049E+01	1.69650E+02	4.64293E+01
8.0000E-03	5.16218E+01	1.79675E+02	4.05957E+01
1.2000E-02	4.59483E+01	1.92110E+02	3.60060E+01
1.6000E-02	4.22143E+01	2.05833E+02	3.22648E+01
2.0000E-02	4.03800E+01	2.19303E+02	2.92168E+01
2.4000E-02	3.98024E+01	2.31242E+02	2.67725E+01
2.8000E-02	3.97071E+01	2.41159E+02	2.48360E+01
3.2000E-02	3.95115E+01	2.49184E+02	2.32829E+01
3.6000E-02	3.89079E+01	2.55713E+02	2.19675E+01
4.0000E-02	3.78146E+01	2.61199E+02	2.07437E+01
4.4000E-02	3.63001E+01	2.66102E+02	1.94856E+01
4.8000E-02	3.45214E+01	2.70893E+02	1.81013E+01
5.2000E-02	3.26875E+01	2.76063E+02	1.65394E+01
5.6000E-02	3.10434E+01	2.82086E+02	1.47914E+01
6.0000E-02	2.98644E+01	2.89311E+02	1.28933E+01
6.4000E-02	2.94388E+01	2.97800E+02	1.09277E+01
6.8000E-02	3.00209E+01	3.07198E+02	9.02194E+00
7.2000E-02	3.17632E+01	3.16821E+02	7.34267E+00
7.6000E-02	3.46755E+01	3.25981E+02	6.08426E+00
8.0000E-02	3.86454E+01	3.34288E+02	5.45953E+00
8.4000E-02	4.34923E+01	3.41706E+02	5.69897E+00
8.8000E-02	4.90068E+01	3.48460E+02	7.06224E+00
9.2000E-02	5.49470E+01	3.54922E+02	9.85744E+00
9.6000E-02	6.09815E+01	1.55964E+00	1.44521E+01
1.0000E-01	6.65543E+01	8.89479E+00	2.12325E+01
1.0400E-01	7.06337E+01	1.74285E+01	3.04010E+01
1.0800E-01	7.13590E+01	2.73291E+01	4.13892E+01
1.1200E-01	6.59851E+01	3.74530E+01	5.17357E+01
1.1600E-01	5.27931E+01	4.27877E+01	5.65986E+01
1.2000E-01	3.76899E+01	3.09005E+01	5.26393E+01
1.2400E-01	3.53411E+01	1.30639E+00	4.36866E+01
1.2800E-01	4.24780E+01	3.43073E+02	3.57686E+01
1.3200E-01	4.81478E+01	3.35325E+02	3.06692E+01
1.3600E-01	5.01821E+01	3.31534E+02	2.77023E+01
1.4000E-01	4.89070E+01	3.29869E+02	2.59504E+01
1.4400E-01	4.46838E+01	3.30560E+02	2.47242E+01
1.4800E-01	3.78293E+01	3.35567E+02	2.34733E+01
1.5200E-01	2.95685E+01	3.50631E+02	2.17033E+01
1.5600E-01	2.55835E+01	2.62070E+01	1.90992E+01
1.6000E-01	3.58081E+01	6.59223E+01	1.60061E+01
1.6400E-01	5.75816E+01	8.84510E+01	1.39807E+01
1.6800E-01	8.39982E+01	1.03387E+02	1.55543E+01
1.7200E-01	1.10829E+02	1.17152E+02	2.34278E+01
1.7600E-01	1.34118E+02	1.32573E+02	4.02678E+01
1.8000E-01	1.47569E+02	1.51709E+02	6.79396E+01
1.8400E-01	1.39130E+02	1.75083E+02	1.00825E+02
1.8800E-01	9.87341E+01	1.92852E+02	1.12899E+02
1.9200E-01	6.45232E+01	1.78706E+02	9.08530E+01
1.9600E-01	6.45096E+01	1.62613E+02	6.78586E+01
2.0000E-01	6.37856E+01	1.62977E+02	5.45813E+01

LINKAGE MECHANISM [DYNAMIC ANALYSIS]

REQUEST NUMBER 4

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 11 RELATIVE TO MARKER 1	ANGLE (DEGREES)
0.0000E+00	1.24890E+01	2.83540E+02
4.0000E-03	4.50840E+00	2.84787E+02
8.0000E-03	3.78699E+00	2.85403E+02
1.2000E-02	6.23563E+00	2.86196E+02
1.6000E-02	9.93223E+00	2.87511E+02
2.0000E-02	1.38022E+01	2.89457E+02
2.4000E-02	1.71849E+01	2.92003E+02
2.8000E-02	1.97024E+01	2.95036E+02
3.2000E-02	2.12128E+01	2.98398E+02
3.6000E-02	2.17726E+01	3.01929E+02
4.0000E-02	2.15897E+01	3.05486E+02
4.4000E-02	2.09704E+01	3.08973E+02
4.8000E-02	2.02661E+01	3.12347E+02
5.2000E-02	1.98237E+01	3.15623E+02
5.6000E-02	1.99412E+01	3.18868E+02
6.0000E-02	2.08319E+01	3.22194E+02
6.4000E-02	2.26035E+01	3.25737E+02
6.8000E-02	2.52594E+01	3.29643E+02
7.2000E-02	2.87286E+01	3.34051E+02
7.6000E-02	3.29184E+01	3.39088E+02
8.0000E-02	3.77747E+01	3.44865E+02
8.4000E-02	4.33297E+01	3.51494E+02
8.8000E-02	4.97282E+01	3.59098E+02
9.2000E-02	5.72261E+01	7.83470E+00
9.6000E-02	6.61459E+01	1.79113E+01
1.0000E-01	7.67225E+01	2.95824E+01
1.0400E-01	8.86597E+01	4.31075E+01
1.0800E-01	1.00041E+02	5.85861E+01
1.1200E-01	1.05469E+02	7.55453E+01
1.1600E-01	9.59417E+01	9.22939E+01
1.2000E-01	6.77000E+01	1.05898E+02
1.2400E-01	3.28281E+01	1.14094E+02
1.2800E-01	5.54113E+00	1.17087E+02
1.3200E-01	1.14689E+01	2.96478E+02
1.3600E-01	2.09121E+01	2.93744E+02
1.4000E-01	2.51779E+01	2.89911E+02
1.4400E-01	2.53271E+01	2.85723E+02
1.4800E-01	2.13163E+01	2.81844E+02
1.5200E-01	1.22827E+01	2.79017E+02
1.5600E-01	2.94869E+00	9.81624E+01
1.6000E-01	2.47154E+01	1.00343E+02
1.6400E-01	5.13927E+01	1.06525E+02
1.6800E-01	8.04302E+01	1.17295E+02
1.7200E-01	1.10987E+02	1.32936E+02
1.7600E-01	1.44585E+02	1.53798E+02
1.8000E-01	1.81802E+02	1.80491E+02
1.8400E-01	2.09496E+02	2.12876E+02
1.8800E-01	1.82762E+02	2.46070E+02
1.9200E-01	9.82860E+01	2.69277E+02
1.9600E-01	3.75350E+01	2.79788E+02
2.0000E-01	1.24890E+01	2.83540E+02

LINKAGE MECHANISM [DYNAMIC ANALYSIS]

REQUEST NUMBER 5

TIME	MAGNITUDE OF THE LINEAR ACCELERATION OF MARKER 9 RELATIVE TO MARKER 1	ANGLE (DEGREES)	MAGNITUDE OF THE ANGULAR ACCELERATION (RADS) OF MARKER 9 RELATIVE TO MARKER 1
0.0000E+00	1.54301E+03	2.90283E+02	-2.50598E+03
4.0000E-03	2.72731E+03	2.96738E+02	-1.67960E+03
8.0000E-03	3.02351E+03	3.01779E+02	-1.27776E+03
1.2000E-02	2.92359E+03	3.06176E+02	-1.03198E+03
1.6000E-02	2.64141E+03	3.10706E+02	-8.44429E+02
2.0000E-02	2.28099E+03	3.16055E+02	-6.83023E+02
2.4000E-02	1.90161E+03	3.22878E+02	-5.43037E+02
2.8000E-02	1.54491E+03	3.31823E+02	-4.30429E+02
3.2000E-02	1.24517E+03	3.43441E+02	-3.52293E+02
3.6000E-02	1.02913E+03	3.57626E+02	-3.11577E+02
4.0000E-02	9.06964E+02	1.26094E+01	-3.05618E+02
4.4000E-02	8.63684E+02	2.51593E+01	-3.27290E+02
4.8000E-02	8.70063E+02	3.28951E+01	-3.67021E+02
5.2000E-02	9.05031E+02	3.55619E+01	-4.14303E+02
5.6000E-02	9.63483E+02	3.43392E+01	-4.58213E+02
6.0000E-02	1.04856E+03	3.09994E+01	-4.87363E+02
6.4000E-02	1.16102E+03	2.72807E+01	-4.90131E+02
6.8000E-02	1.29464E+03	2.43866E+01	-4.55743E+02
7.2000E-02	1.43894E+03	2.28598E+01	-3.75748E+02
7.6000E-02	1.58457E+03	2.28161E+01	-2.44584E+02
8.0000E-02	1.72675E+03	2.42673E+01	-5.82284E+01
8.4000E-02	1.86624E+03	2.73656E+01	1.88681E+02
8.8000E-02	2.00909E+03	3.25491E+01	5.05723E+02
9.2000E-02	2.16682E+03	4.06061E+01	9.07301E+02
9.6000E-02	2.35825E+03	5.26460E+01	1.40684E+03
1.0000E-01	2.60946E+03	6.99294E+01	1.99405E+03
1.0400E-01	2.93473E+03	9.36390E+01	2.57157E+03
1.0800E-01	3.27097E+03	1.25358E+02	2.82482E+03
1.1200E-01	3.50518E+03	1.69119E+02	2.13171E+03
1.1600E-01	4.06133E+03	2.24709E+02	1.22098E+02
1.2000E-01	4.88433E+03	2.67456E+02	-1.91071E+03
1.2400E-01	4.29041E+03	2.88235E+02	-2.27982E+03
1.2800E-01	2.78257E+03	2.93942E+02	-1.62124E+03
1.3200E-01	1.45516E+03	2.86702E+02	-9.66189E+02
1.3600E-01	5.83362E+02	2.48980E+02	-5.56484E+02
1.4000E-01	7.11773E+02	1.61025E+02	-3.47568E+02
1.4400E-01	1.47442E+03	1.32664E+02	-2.88034E+02
1.4800E-01	2.43709E+03	1.20142E+02	-3.58390E+02
1.5200E-01	3.63056E+03	1.12921E+02	-5.41825E+02
1.5600E-01	5.02876E+03	1.10274E+02	-7.48932E+02
1.6000E-01	6.43046E+03	1.13273E+02	-7.31709E+02
1.6400E-01	7.57507E+03	1.23027E+02	-1.70901E+02
1.6800E-01	8.46487E+03	1.39862E+02	1.07040E+03
1.7200E-01	9.43317E+03	1.63986E+02	2.97766E+03
1.7600E-01	1.10896E+04	1.96087E+02	5.54182E+03
1.8000E-01	1.39143E+04	2.36441E+02	8.14254E+03
1.8400E-01	1.58098E+04	2.88014E+02	7.13154E+03
1.8800E-01	1.26404E+04	2.12415E+00	-2.07938E+03
1.9200E-01	7.77882E+03	6.80930E+01	-6.89825E+03
1.9600E-01	1.65785E+03	9.43853E+01	-4.37040E+03
2.0000E-01	1.54301E+03	2.90283E+02	-2.50598E+03

REQUEST NUMBER 6

TIME	MAGNITUDE OF THE LINEAR ACCELERATION OF MARKER 11 RELATIVE TO MARKER 1	ANGLE (DEGREES)
0.0000E+00	3.52978E+03	1.01732E+02
4.0000E-03	8.41658E+02	1.03798E+02
8.0000E-03	3.24234E+02	2.87213E+02
1.2000E-02	8.25317E+02	2.88125E+02
1.6000E-02	9.82716E+02	2.91623E+02
2.0000E-02	9.37629E+02	2.97801E+02
2.4000E-02	7.77251E+02	3.07750E+02
2.8000E-02	5.76031E+02	3.23809E+02
3.2000E-02	4.08941E+02	3.50209E+02
3.6000E-02	3.40508E+02	2.58669E+01
4.0000E-02	3.52049E+02	5.44502E+01
4.4000E-02	3.62230E+02	6.88423E+01
4.8000E-02	3.32790E+02	7.05182E+01
5.2000E-02	2.85389E+02	5.60225E+01
5.6000E-02	3.08050E+02	2.60957E+01
6.0000E-02	4.53189E+02	5.35050E+00
6.4000E-02	6.64407E+02	3.59054E+02
6.8000E-02	8.94377E+02	2.77642E-01
7.2000E-02	1.12734E+03	5.58059E+00
7.6000E-02	1.37094E+03	1.34618E+01
8.0000E-02	1.65021E+03	2.30092E+01
8.4000E-02	2.00143E+03	3.35640E+01
8.8000E-02	2.46849E+03	4.47866E+01
9.2000E-02	3.10282E+03	5.67627E+01
9.6000E-02	3.96043E+03	7.00134E+01
1.0000E-01	5.07804E+03	8.54745E+01
1.0400E-01	6.38954E+03	1.04597E+02
1.0800E-01	7.54789E+03	1.29869E+02
1.1200E-01	7.94639E+03	1.66400E+02
1.1600E-01	8.18718E+03	2.18870E+02
1.2000E-01	9.25169E+03	2.65175E+02
1.2400E-01	8.15532E+03	2.88678E+02
1.2800E-01	5.46007E+03	2.96857E+02
1.3200E-01	3.18167E+03	2.94786E+02
1.3600E-01	1.67202E+03	2.82976E+02
1.4000E-01	6.99469E+02	2.49568E+02
1.4400E-01	6.50225E+02	1.50525E+02
1.4800E-01	1.61467E+03	1.13440E+02
1.5200E-01	2.99095E+03	1.01082E+02
1.5600E-01	4.64736E+03	9.82390E+01
1.6000E-01	6.17933E+03	1.04393E+02
1.6400E-01	7.30212E+03	1.21497E+02
1.6800E-01	8.74676E+03	1.49184E+02
1.7200E-01	1.18425E+04	1.80921E+02
1.7600E-01	1.74042E+04	2.12886E+02
1.8000E-01	2.53564E+04	2.49092E+02
1.8400E-01	3.14484E+04	2.98317E+02
1.8800E-01	2.91552E+04	1.11523E+01
1.9200E-01	2.17499E+04	7.07805E+01
1.9600E-01	9.91094E+03	9.39606E+01
2.0000E-01	3.52978E+03	1.01732E+02

LINKAGE MECHANISM [DYNAMIC ANALYSIS]

REQUEST NUMBER 7

TIME	MAGNITUDE OF THE FORCE EXERTED ON MARKER 2 BY MARKER 1	ANGLE (DEGREES)	MAGNITUDE OF THE TORQUE EXERTED ON MARKER 2 BY MARKER 1
0.0000E+00	4.93493E+00	7.02082E+01	1.19122E+01
4.0000E-03	5.26333E+00	7.59582E+01	1.10501E+01
8.0000E-03	5.30323E+00	7.67621E+01	9.81436E+00
1.2000E-02	5.11609E+00	7.59444E+01	8.32017E+00
1.6000E-02	4.82266E+00	7.41368E+01	6.85586E+00
2.0000E-02	4.50236E+00	7.14677E+01	5.58760E+00
2.4000E-02	4.20157E+00	6.80265E+01	4.56676E+00
2.8000E-02	3.94560E+00	6.39703E+01	3.77243E+00
3.2000E-02	3.74561E+00	5.95237E+01	3.14853E+00
3.6000E-02	3.60285E+00	5.49287E+01	2.63077E+00
4.0000E-02	3.51237E+00	5.03847E+01	2.16315E+00
4.4000E-02	3.46630E+00	4.60114E+01	1.70498E+00
4.8000E-02	3.45597E+00	4.18473E+01	1.23112E+00
5.2000E-02	3.47244E+00	3.78734E+01	7.28602E-01
5.6000E-02	3.50599E+00	3.40467E+01	1.92806E-01
6.0000E-02	3.54547E+00	3.03261E+01	-3.74971E-01
6.4000E-02	3.57839E+00	2.66862E+01	-9.67877E-01
6.8000E-02	3.59272E+00	2.31181E+01	-1.57313E+00
7.2000E-02	3.57971E+00	1.96233E+01	-2.17316E+00
7.6000E-02	3.53660E+00	1.62074E+01	-2.74952E+00
8.0000E-02	3.46756E+00	1.28793E+01	-3.28892E+00
8.4000E-02	3.38334E+00	9.65522E+00	-3.78931E+00
8.8000E-02	3.30075E+00	6.56379E+00	-4.26529E+00
9.2000E-02	3.24276E+00	3.63955E+00	-4.75199E+00
9.6000E-02	3.23657E+00	8.75950E-01	-5.30096E+00
1.0000E-01	3.29724E+00	3.58088E+02	-5.93831E+00
1.0400E-01	3.35841E+00	3.54661E+02	-6.49254E+00
1.0800E-01	3.08279E+00	3.49179E+02	-6.13844E+00
1.1200E-01	1.69961E+00	3.36754E+02	-3.06989E+00
1.1600E-01	1.12083E+00	1.72285E+02	2.82294E+00
1.2000E-01	2.82893E+00	1.45400E+02	5.56296E+00
1.2400E-01	2.13764E+00	1.27548E+02	3.37826E+00
1.2800E-01	9.32210E-01	1.32506E+02	1.84864E+00
1.3200E-01	9.26587E-01	1.95620E+02	2.16025E+00
1.3600E-01	1.89125E+00	2.09192E+02	3.28204E+00
1.4000E-01	3.09304E+00	2.08799E+02	4.60231E+00
1.4400E-01	4.60594E+00	2.07342E+02	5.81208E+00
1.4800E-01	6.60233E+00	2.06469E+02	6.58158E+00
1.5200E-01	9.26025E+00	2.06320E+02	6.35291E+00
1.5600E-01	1.26006E+01	2.06760E+02	4.23764E+00
1.6000E-01	1.61885E+01	2.07635E+02	-6.65103E-01
1.6400E-01	1.91723E+01	2.08869E+02	-8.34960E+00
1.6800E-01	2.09569E+01	2.10476E+02	-1.75669E+01
1.7200E-01	2.14849E+01	2.12489E+02	-2.66173E+01
1.7600E-01	2.10150E+01	2.14808E+02	-3.40388E+01
1.8000E-01	1.91841E+01	2.16526E+02	-3.71608E+01
1.8400E-01	9.78958E+00	2.10697E+02	-1.94931E+01
1.8800E-01	1.21758E+01	4.63851E+01	3.06638E+01
1.9200E-01	1.19481E+01	3.52094E+01	2.92526E+01
1.9600E-01	5.46101E+00	4.90863E+01	1.45630E+01
2.0000E-01	4.93493E+00	7.02082E+01	1.19122E+01

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* PROGRAMMER     : DEEPAK N. RODE
*
* DATE WRITTEN   : OCTOBER 1, 1987
*
* OBJECTIVE      : TO DETERMINE THE DISPLACEMENTS,VELOCITIES AND
*                  ACCELERATIONS OF LINK 6 AND LINK 7 OF THE LINKAGE
*                  MECHANISM. ALSO FIND THE TORQUE AT LINK 2.
*
* DESCRIPTION OF VARIABLES:
*
*
*          MAXN    = MAXIMUM NUMBER OF STEPS.
*          R2      = LENGTH OF LINK 2.
*          R3      = LENGTH OF LINK 3 (ARM 1).
*          R4      = LENGTH OF LINK 4.
*          R5      = LENGTH OF LINK 3 (ARM 2).
*          R6      = LENGTH OF LINK 6.
*          R7      = LENGTH OF LINK 7.
*          R8      = LENGTH BETWEEN THE POINTS G AND F.
*          T2      = ANGLE THETA 2.
*          T3      = ANGLE THETA 3.
*          T4      = ANGLE THETA 4.
*          T5      = ANGLE THETA 5.
*          T6      = ANGLE THETA 6.
*          T7      = ANGLE THETA 7.
*          CI      = ANGLE CI.
*          W2      = ANGULAR VELOCITY OF LINK 2.
*          W3      = ANGULAR VELOCITY OF LINK 3.
*          W4      = ANGULAR VELOCITY OF LINK 4.
*          W5      = ANGULAR VELOCITY OF LINK 5.
*          W6      = ANGULAR VELOCITY OF LINK 6.
*          W7      = ANGULAR VELOCITY OF LINK 7.
*          V7      = LINEAR VELOCITY OF LINK 7.
*          A3      = ANGULAR ACCELERATION OF LINK 3.
*          A4      = ANGULAR ACCELERATION OF LINK 4.
*          A5      = ANGULAR ACCELERATION OF LINK 5.
*          A6      = ANGULAR ACCELARATION OF LINK 6.
*          A7      = ANGULAR ACCELARATION OF LINK 7.
*          A7N     = NORMAL COMPONENT OF ACCELERATION OF LINK 7.
*          A7T     = TANGENTIAL COMPONENT OF ACCELERATION OF LINK 7.
*          A7L     = LINEAR ACCELERATION OF LINK 7.
*          TIME    = TIME STEP.
*          WE2     = WEIGHT OF LINK 2.
*          WE3     = WEIGHT OF LINK 3.
*          WE4     = WEIGHT OF LINK 4.
*          WE6     = WEIGHT OF LINK 6.
*          WE7     = WEIGHT OF LINK 7.
*          M2      = MASS OF LINK 2.
*          M3      = MASS OF LINK 3.
*          M4      = MASS OF LINK 4.
*          M6      = MASS OF LINK 6.
*          M7      = MASS OF LINK 7.
*          I2      = MASS MOMENT OF INERTIA OF LINK 2.
*          I3      = MASS MOMENT OF INERTIA OF LINK 3.
*          I4      = MASS MOMENT OF INERTIA OF LINK 4.
*          I6      = MASS MOMENT OF INERTIA OF LINK 6.
*          I7      = MASS MOMENT OF INERTIA OF LINK 7.
*          TS2     = TORQUE AT LINK 2.
*
* WORK VARIABLES:
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*
*       A,B,A1,B1,A2,B2,U1,V1,U2,V2,U3,V3,P1,P2,P3,P4,P5,P6,P7,P8
*       ,P9,P10,T44,T77,AS,AS1,AS2,BQ,BQ1,BQ2,PR,PR1,PR2,BS,BS1,BS2,
*       OQ,OQ1,OQ2,OP,OP1,OP2
*
* COMMENTS :
*
*       NONE.
*
*
        PARAMETER (MAXN=51)
        REAL*4 R1,R2,R3,R4,R5,R6,R7,R8,R9
        REAL*4 T2,T3,T4,T5,T6,T7,T77,T44,GAMA,BETA,CI
        REAL*4 P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,TIME
        REAL*4 W2,W3,W4,W5,W6,W7,V7,A3,A4,A5,A6,A7,A7N,A7T,A7L,U,V
        REAL*4 WE2,WE3,WE4,WE6,WE7,I2,I3,I4,I6,I7,G,M2,M3,M4,M6,M7
        REAL*4 AS,AS1,AS2,X33,Y33,TS2,X2,YY3,XX3,X4,X7
        REAL*4 X6,XX6,Y6,YY6
        LOGICAL*1 SUCCESS
*
        READ (5,*) R1,R2,R3,R4,R5,R6,R7,R8
        READ (5,*) T2,CI,W2,TIME
        READ (5,*) WE2,WE3,WE4,WE6,WE7
        READ (5,*) I2,I3,I4,I6,I7,G
*
        WRITE (6,15)
 15     FORMAT(8X,'TIME',7X,'T2',10X,'T3',9X,'T4',8X,'T6',10X,'T7',
     /  9X,'W6',9X,'V7',8X,'A6',8X,'A7L',8X,'TS2',/)
*
        DO 10 K=1,MAXN
*
             A = R1-R2*COSD(T2)
             B = -R2*SIND(T2)
          GAMA = ATAN2D(B,A)
*
            B1 = SQRT(4.0*(R4**2)*(A**2+B**2)-
     /   (-A**2-B**2-R4**2+R3**2)**2)
            A1 = (-A**2-B**2-R4**2+R3**2)
           T44 = ATAN2D(B1,A1)
            T4 = T44+GAMA
*
            A2 = A+R4*COSD(T4)
            B2 = B+R4*SIND(T4)
            T3 = ATAN2D(B2,A2)
*
            W3 = -R2*W2*(SIND(T2-T4))/(R3*(SIND(T3-T4)))
            W4 = R2*W2*(SIND(T3-T2))/(R4*(SIND(T3-T4)))
*
            A3 = (-R2*(W2**2)*(COSD(T2-T4))-R3*(W3**2)*
     /   (COSD(T3-T4))+R4*(W4**2))/(R3*SIND(T3-T4))
            A4 = (-R2*(W2**2)*(COSD(T2-T3))+R4*(W4**2)*
     /   (COSD(T3-T4))-R3*(W3**2))/(R4*SIND(T3-T4))
*
            T5 = 300.0+T3
            U1 = R8*COSD(CI)-R4*COSD(T4)-R5*COSD(T5)
            V1 = R8*SIND(CI)-R4*SIND(T4)-R5*SIND(T5)
          BETA = ATAN2D(V1,U1)
*
            U2 = U1**2+V1**2+R7**2-R6**2
            V2 = SQRT((4.0*(R7**2)*(U1**2+V1**2))-(U1**2+
```

```
     /    V1**2+R7**2-R6**2)**2)
            T77 = ATAN2D(V2,U2)
             T7 = T77+BETA
*
             U3 = V1-R7*SIND(T7)
             V3 = U1-R7*COSD(T7)
             T6 = ATAN2D(U3,V3)
*
             T5 = 300.0+T3
*
             W5 = W3
*
             P1 = R4*(SIND(T4)*W4)+R5*(SIND(T5)*W5)
             P2 = -R4*COSD(T4)*W4-R5*(COSD(T5)*W5)
             P3 = P1*R7*(COSD(T7))+R7*P2*SIND(T7)
             P4 = -R6*R7*(SIND(T6-T7))
             P5 = -P2*(R6)*SIND(T6)-P1*R6*COSD(T6)
*
             W6 = P3/P4
             W7 = P5/P4
             V7 = R7*W7
             A5 = A3
*
             P6 = R4*(-COSD(T4)*(W4**2))+R4*(-SIND(T4)*A4)-R5*
     /    COSD(T5)*(W5**2)-R5*(SIND(T5)*(A5))-R6*(COSD(T6)*
     /    (W6**2))-R7*(COSD(T7)*(W7**2))
             P7 = R4*(-SIND(T4)*(W4**2))+R4*(COSD(T4)*(A4))-R5*
     /    (SIND(T5)*(W5**2))+R5*(COSD(T5)*A5)-R6*
     /    (SIND(T6)*(W6**2))-R7*(SIND(T7)*(W7**2))
             P8 = -P6*R7*COSD(T7)-(R7*SIND(T7)*P7)
             P9 = -R6*R7*SIND(T6-T7)
            P10 = P7*R6*SIND(T6)+P6*R6*COSD(T6)
*
             A6 = P8/P9
             A7 = P10/P9
            A7N = R7*(W7**2)
            A7T = R7*A7
            A7L = SQRT(A7N**2+A7T**2)
*
             M2 = WE2/G
             M3 = WE3/G
             M4 = WE4/G
             M6 = WE6/G
             M7 = WE7/G
             W3 = W5
             A3 = A5
*
             X2 = (R2/2.0)*COSD(T2)*W2
            XX2 = (R2/2.0)*(-SIND(T2))*(W2**2)
             Y2 = (R2/2.0)*(-SIND(T2))*W2
            YY2 = (R2/2.0)*(-COSD(T2))*(W2**2)
*
             AS = R2*COSD(T2)
            AS1 = R2*(-SIND(T2))*W2
            AS2 = R2*(-COSD(T2))*(W2**2)
*
             BQ = (7.3)*COSD(T3)
            BQ1 = (7.3)*(-SIND(T3))*W3
            BQ2 = (7.3)*((-COSD(T3))*(W3**2)+(-SIND(T3))*A3)
*
```

```
         PR  = (2.6)*SIND(T3)
        PR1  = (2.6)*COSD(T3)*W3
        PR2  = (2.6)*((-SIND(T3))*(W3**2)+COSD(T3)*A3)
*
        Y33  = BQ+AS+PR
         Y3  = AS1+BQ1+PR1
        YY3  = AS2+BQ2+PR2
*
         BS  = R2*SIND(T2)
        BS1  = R2*COSD(T2)*W2
        BS2  = R2*((-SIND(T2))*(W2**2))
*
         OQ  = (7.3)*SIND(T3)
        OQ1  = (7.3)*COSD(T3)*W3
        OQ2  = (7.3)*((-SIND(T3))*(W3**2)+COSD(T3)*A3)
*
         OP  = (2.6)*COSD(T3)
        OP1  = (2.6)*(-SIND(T3))*W3
        OP2  = (2.6)*((-COSD(T3))*(W3**2)+(-SIND(T3))*A3)
*
        X33  = BS+OQ-OP
         X3  = BS1+OQ1-OP1
        XX3  = BS2+OQ2-OP2
*
         X4  = (R4/2.0)*COSD(T4)*W4
         X7  = (-R7/2.0)*COSD(T7)*W7
*
        T66  = T6+180.0
*
         X6  = -R7*COSD(T7)*W7+(R6/2.0)*COSD(T66)*W6
        XX6  = -R7*(-SIND(T7))*(W7**2)-R7*COSD(T7)*A7+(R6/2.0)
     /  *(-SIND(T66))*(W6**2)+(R6/2.0)*(COSD(T66))*A6
*
         Y6  = (R6/2.0)*(-SIND(T66))*W6-R7*(-SIND(T7))*W7
        YY6  = (R6/2.0)*(-COSD(T66))*(W6**2)+(R6/2.0)*
     /  (-SIND(T66))*A6-R7*(-COSD(T7))*(W7**2)-R7*(-SIND(T7))
     /  *A7
*
        TS2  = I3*A3*W3+(I4+(M4*((R4/2.)**2)))*A4*W4+I6*A6
     /  *W6+(I7+(M7*((R7/2.0)**2)))*A7*W7+WE2*X2+(M3*XX3+WE3)
     /  *X3+M3*YY3*Y3+WE4*X4+(M6*XX6+WE6)*X6+M6*YY6*Y6+
     /  WE7*X7
        TS2  = TS2/W2
*
        IF(TIME .GE. 0.187999) THEN
            T6 = T6+180.0
            T6 = T6+360.0
        ELSE
            T6 = T6+180.0
        END IF
*
        IF(TIME .GT. 0.11599 .AND. TIME .LT. 0.18199) THEN
            T7 = T7+180.0
            T7 = T7-360.0
        ELSE IF(TIME .GT. 0.18399) THEN
            T7 = T7+180.0
        ELSE
            T7 = T7+180.0
        END IF
*
```

```
        WRITE(6,20) TIME,T2,T3,T4,T6,T7,W6,V7,A6,A7L,TS2
20      FORMAT(2X,11(1X,F10.4))
*
            T2 = T2-7.2
*
          TIME = TIME+0.004

10      END DO

        SUCCESS= .TRUE.

        END
```

TIME	T2	T3	T4	T6	T7
0.0000	315.0000	53.6465	93.2790	64.2601	193.5402
0.0040	307.8000	55.2597	97.5265	75.7728	194.7868
0.0080	300.6000	56.3508	101.3757	85.7147	195.4029
0.0120	293.4000	56.9476	104.8025	94.4740	196.1961
0.0160	286.2000	57.0924	107.8045	102.2829	197.5112
0.0200	278.9999	56.8345	110.3919	109.3159	199.4567
0.0240	271.7999	56.2257	112.5819	115.7211	202.0030
0.0280	264.5999	55.3168	114.3941	121.6264	205.0356
0.0320	257.3999	54.1561	115.8483	127.1344	208.3984
0.0360	250.1999	52.7886	116.9629	132.3166	211.9286
0.0400	242.9999	51.2555	117.7542	137.2105	215.4861
0.0440	235.7999	49.5945	118.2363	141.8222	218.9734
0.0480	228.5999	47.8395	118.4215	146.1323	222.3473
0.0520	221.3999	46.0213	118.3199	150.1055	225.6229
0.0560	214.1999	44.1673	117.9407	153.6991	228.8683
0.0600	206.9999	42.3020	117.2918	156.8737	232.1942
0.0640	199.7999	40.4469	116.3810	159.6037	235.7371
0.0680	192.5999	38.6210	115.2161	161.8871	239.6430
0.0720	185.3999	36.8405	113.8053	163.7562	244.0516
0.0760	178.1999	35.1190	112.1581	165.2849	249.0881
0.0800	170.9999	33.4680	110.2848	166.5934	254.8654
0.0840	163.7999	31.8968	108.1974	167.8532	261.4937
0.0880	156.5999	30.4127	105.9095	169.2914	269.0976
0.0920	149.3999	29.0214	103.4362	171.1996	277.8348
0.0960	142.2000	27.7272	100.7945	173.9471	287.9114
0.1000	135.0000	26.5335	98.0029	177.9913	299.5825
0.1040	127.8000	25.4432	95.0817	183.8636	313.1076
0.1080	120.6000	24.4589	92.0531	192.0700	328.5862
0.1120	113.4000	23.5834	88.9410	202.7935	345.5455
0.1160	106.2000	22.8203	85.7718	215.3630	2.2939
0.1200	99.0000	22.1744	82.5741	228.0389	15.8983
0.1240	91.8000	21.6520	79.3803	239.1038	24.0945
0.1280	84.6000	21.2621	76.2267	248.1569	27.0874
0.1320	77.4000	21.0163	73.1548	255.7199	26.4776
0.1360	70.2000	20.9305	70.2132	262.3777	23.7438
0.1400	63.0000	21.0252	67.4590	268.5098	19.9109
0.1440	55.8000	21.3266	64.9604	274.3122	15.7230
0.1480	48.6000	21.8679	62.7984	279.8406	11.8442
0.1520	41.4000	22.6889	61.0692	285.0316	9.0173
0.1560	34.2000	23.8355	59.8834	289.7234	8.1624
0.1600	27.0000	25.3561	59.3627	293.7453	10.3435
0.1640	19.8000	27.2931	59.6291	297.1389	16.5246
0.1680	12.6000	29.6698	60.7848	300.4284	27.2948
0.1720	5.4000	32.4726	62.8838	304.7498	42.9357
0.1760	-1.8000	35.6344	65.9025	311.8524	63.7984
0.1800	-9.0000	39.0300	69.7250	324.0493	90.4912
0.1840	-16.2000	42.4892	74.1539	343.4552	122.8765
0.1880	-23.4000	45.8268	78.9468	368.6719	156.0702
0.1920	-30.6000	48.8753	83.8613	392.3889	179.2770
0.1960	-37.8000	51.5077	88.6902	410.3712	189.7883
0.2000	-45.0000	53.6465	93.2790	424.2601	193.5402

TIME	W6	V7	A6	A7L	TS2
0.0000	54.5814	12.4891	-2505.9810	3529.7937	11.9122
0.0040	46.4293	4.5084	-1679.5970	841.6552	11.0501
0.0080	40.5957	3.7870	-1277.7545	324.2376	9.8144
0.0120	36.0060	6.2357	-1031.9847	825.3171	8.3202
0.0160	32.2648	9.9323	-844.4285	982.7147	6.8559
0.0200	29.2168	13.8022	-683.0233	937.6296	5.5876
0.0240	26.7725	17.1850	-543.0358	777.2500	4.5668
0.0280	24.8360	19.7025	-430.4284	576.0306	3.7724
0.0320	23.2829	21.2128	-352.2924	408.9398	3.1485
0.0360	21.9675	21.7726	-311.5766	340.5088	2.6308
0.0400	20.7437	21.5898	-305.6177	352.0508	2.1631
0.0440	19.4856	20.9704	-327.2907	362.2294	1.7050
0.0480	18.1013	20.2661	-367.0220	332.7893	1.2311
0.0520	16.5394	19.8238	-414.3034	285.3889	0.7286
0.0560	14.7913	19.9412	-458.2136	308.0518	0.1928
0.0600	12.8933	20.8320	-487.3630	453.1909	-0.3750
0.0640	10.9277	22.6035	-490.1315	664.4089	-0.9679
0.0680	9.0219	25.2594	-455.7433	894.3796	-1.5731
0.0720	7.3427	28.7286	-375.7472	1127.3445	-2.1732
0.0760	6.0842	32.9185	-244.5824	1370.9418	-2.7495
0.0800	5.4595	37.7747	-58.2267	1650.2135	-3.2889
0.0840	5.6990	43.3297	188.6839	2001.4346	-3.7893
0.0880	7.0623	49.7283	505.7268	2468.4973	-4.2653
0.0920	9.8575	57.2262	907.3052	3102.8245	-4.7520
0.0960	14.4522	66.1460	1406.8438	3960.4407	-5.3010
0.1000	21.2326	76.7227	1994.0597	5078.0615	-5.9383
0.1040	30.4011	88.6598	2571.5750	6389.5415	-6.4925
0.1080	41.3893	100.0411	2824.8174	7547.8867	-6.1384
0.1120	51.7359	105.4692	2131.7036	7946.4209	-3.0699
0.1160	56.5986	95.9415	122.0840	8187.1743	2.8229
0.1200	52.6393	67.6998	-1910.7203	9251.6895	5.5629
0.1240	43.6866	32.8278	-2279.8206	8155.3179	3.3782
0.1280	35.7686	5.5411	-1621.2406	5460.0659	1.8486
0.1320	30.6692	-11.4689	-966.1859	3181.6638	2.1603
0.1360	27.7022	-20.9122	-556.4813	1672.0143	3.2820
0.1400	25.9504	-25.1779	-347.5679	699.4679	4.6023
0.1440	24.7242	-25.3271	-288.0341	650.2256	5.8121
0.1480	23.4733	-21.3163	-358.3897	1614.6737	6.5816
0.1520	21.7033	-12.2828	-541.8259	2990.9575	6.3529
0.1560	19.0992	2.9487	-748.9323	4647.3691	4.2376
0.1600	16.0061	24.7155	-731.7085	6179.3325	-0.6651
0.1640	13.9807	51.3927	-170.8983	7302.1221	-8.3496
0.1680	15.5543	80.4303	1070.4045	8746.7666	-17.5669
0.1720	23.4278	110.9872	2977.6626	11842.5264	-26.6172
0.1760	40.2679	144.5849	5541.8218	17404.1934	-34.0387
0.1800	67.9397	181.8016	8142.5332	25356.3906	-37.1607
0.1840	100.8248	209.4954	7131.5142	31448.3418	-19.4930
0.1880	112.8986	182.7619	-2079.4009	29155.2207	30.6638
0.1920	90.8529	98.2859	-6898.2412	21749.9102	29.2525
0.1960	67.8585	37.5349	-4370.3813	9910.8965	14.5629
0.2000	54.5813	12.4891	-2505.9766	3529.7788	11.9122

XII. APPENDIX C: SIMPLIFIED VERSION OF THE DRAM USER MANUAL

Simplfied Version

Of

the DRAM User Manual

***

The user's manual has been written with the guidance of Dr. Wayne Walter and Dr. Richard Budynas. My special thanks to them.

***

Deepak Namdeo Rode

AUGUST, 1986

TABLE OF CONTENTS

PAGE

PAGE

CHAPTER 1 : INTRODUCTION TO DRAM

1.1 INTRODUCTION:

This DRAM user manual explains how to use DRAM for the analysis of different types of mechanical systems. DRAM also has the capability to handle the computer-aided-design of mechanical systems and has been written in the FORTRAN IV language. DRAM is the abbreviation for Dynamic Response of Articulated Machinery.

The manual includes several types of examples. Each example is defined explicitly along with documentation which helps the reader to understand the DRAM coding. The manual also tries to explain the difficult portions of DRAM by giving sample examples whenever needed. The sequence of the chapters has been selected such that a smooth understanding should be obtained.

Additionally, the manual has included chapters on how to get started with DRAM and DRAM GRAPHICS on the VAX/VMS system. DRAM GRAPHICS can be done on the Tektronix-4114 series terminal or the VT-240 terminal (in the Tektronix-4010 mode). The terminal set-up procedure for graphics has been described in this manual. Common mistakes and difficulties which might occur while running DRAM are given under the chapter "MISCELLANEOUS".

This manual is a simplified version of the Mechanical Dynamic Inc's user guide.

1.2 PROBLEM TYPES:

DRAM provides a solution to systems consisting of zero degree-of-freedom as well as multi-degrees of freedom. However, DRAM does not accept two curved surfaces which possess sliding contact.

DRAM is applicable for the following types of systems or problems:

1. Nonlinear mechanical systems which undergo large displacements.
2. Closed loop (Such as a slider crank etc.) mechanical systems which undergo displacements.
3. Systems whose motion is caused by an external force.
4. Vibrating systems. The vibrating system could be a forced vibration or a free vibration system.
5. Determination of a static equilibrium configuration.
6. Static balancing problem.
7. General problems with specified differential equations.

CHAPTER 2 : INPUT DATA REQUIREMENTS

The rules to be used for DRAM input data coding are described in this chapter. DRAM input data must not exceed 80 characters in length per line/card. Each DRAM statement must be on a separate line/card, and can not be longer than 200 characters after continuing on the next line/lines.

2.1 CONTINUATION OF LINES/CARDS:

In input data coding, there may be an instance where the input data statement requires more than one line/card. That is, the statement needs to continue on the next line. A statement can be continued on the next line/card by either putting a comma (,) in the first column of the second line/card or printing the statement type with its ID on the second line/card followed by the remaining arguments of the statement. The argument must be completed on the same line and can not be written partially on the next line.

<u>For Example:</u>

```
PART/1,MASS=0.5,INERTIA=0.01,ANGLE=90
,DEGDANGLE=18000
OR
PART/1,MASS=0.5,INERTIA=0.01,ANGLE=90
PART/1,DEGDANGLE=18000
```

The above alternatives are the two ways of continuing the line/card for any type of DRAM statement. An example of an unacceptable statement is:

```
PART/1,MASS=0.5,INERTIA=0.01,ANGLE=90,DEG
,DANGLE=18000
```

This is not allowed since the argument DEGDANGLE is split. Similarly, the numerical values of arguments can not be broken.

2.2 EMBEDDED BLANKS:

All DRAM statements must begin within the first five columns of a line/card in order to be considered a data line/card. Additionally, any five consecutive blanks result in the termination of the statement. Hence, a comment can be written in the statement by inserting five consecutive blanks before it starts. Blanks are allowed anywhere in the statement as long as the blanks do not exceed four blanks. Spacing can be allowed between two statements by providing blank lines.

2.3 CODING OF "PROGRAM NAME" AND "LIST" STATEMENTS IN A INPUT DATA DECK:

The first line/card in a DRAM data deck must be a program name or otherwise blank. The first line/card of a DRAM data deck does not execute any DRAM input data statement. DRAM executes all input data statements from the second line/card onwards. The second data card must be a "LIST" statement, if it is desired in the program. The LIST statement provides the listing of a DRAM input language program in the output file. The LIST statement may, however, be eliminated if the program listing is not required.

2.4 COMMENTS:

Comments must be started by keeping the first five columns blank. Comments may be written in a statement line/card by preceeding them with five blanks. There is no limit to the number of comment lines/cards in a data deck.

2.5 ENTRY SEPARATION ON A LINE/CARD:

All KEYWORD=VALUE pairs must be separated from each other by a single comma. As an example, the PAR=PAR1, PAR2,......PARN entry must also be separated by a comma as shown, where PAR1,PAR2... are the numerical values of the PAR keyword. It is not necessary to follow the last data element on a line/card with a comma.

<u>For Example:</u>

PART/2,MASS=50,CM=2,INERTIA=0.15,ANGLE=0,

where MASS=50,CM=2,INERTIA=0.15....etc. are separated by commas. It is not necessary to type a comma after the last element "0".

2.6 IMPLIED ZERO:

If no value for the keyword is assigned, it will be considered as a zero.

For Example:

PART/5,MASS,CM=2,INERTIA,ANGLE=0

Since no values for the mass and mass moment of inertia are assigned, DRAM will consider zero values for the mass and mass moment of inertia.

2.7 NUMBERS:

Numerical values are made up of a string of characters "0-9". An optional plus or minus sign can be written before the first digit of the numerical value. Blanks may appear before or after any numerical value. The statement will be terminated if more than four blanks appear in the statement. Examples of some valid numbers are as follows:

1986	.1986	-19.86
1986.	+19.86	

Numerical values can also be written in an optional exponent form. Examples of some valid real numbers with exponents are as follows:

0.123456E1	123.456E-02	123456E-2

The "E" is consistent with Fortran and symbolizes a real value of single precision. In DRAM, all real values are stored in double precision. If the real number does not have a decimal point, DRAM will assume the decimal point immediately to the right of the last digit.

If a keyword representing an integer value is assigned a decimal value, only the integer part of the number is stored and the fraction is ignored.

For Example:

I=20.2

The keyword I will have value 20 instead of 20.2 . The fraction is ignored.

2.8 DEGREES-OF-FREEDOM OF THE SYSTEM:

DRAM defines the degree-of-freedom of the system in a slightly different manner than the standard definition of the degree-of-freedom of a system. DRAM uses the following definition for the computation of the degree-of-freedom of the system.

$$Nf = 3(Np-1)-2(Nc)-Na$$

where Nf = System degree-of-freedom.

Np = Total number of parts of the system including the ground part.

Nc = Total number of contacts (translational & or rotational) in the system.

Na = Total number of generators in the system. A generator causes motion of the mechanical system. More than one generator may be used in a system.

For Example:

In the six-bar linkage mechanism as shown in Figure 7.13 of example 7.5 of chapter 7, Np=6, Nc=7, Na=1.

$$Nf = 3(6-1)-2(7)-1$$

$= 15-15$

$= 0$

Hence the six-bar linkage mechanism has zero degree-of-freedom although it has one degree of freedom by the standard definition of degree-of-freedom. This formula may fail for certain mechanisms such as those having passive (ineffective constraint force) constraints. Refer to any Statics/Dynamics book for passive constraints.

If the system has zero degree-of-freedom, the system is considered as a kinematic system. Whereas, if the system has greater than zero degree-of-freedom, the system is considered as a dynamic system. Less computational time is required for a kinematic system (algebraic solution). A dynamic system requires numerical integration techniques. The numerical integration techniques consume more computer time than an algebraic solution.

CHAPTER 3 : DEFINITIONS OF DRAM INPUT STATEMENTS:

This chapter deals with definitions of DRAM statements used in input data language programming. A reader should refer to chapter 7 while reading this chapter.

3.1 KEYWORDS:

There are two types of keywords used in DRAM.

1. A keyword which assigns a numeric value after the equal sign.

For Example:

```
I= 3, PAR= 10
```

where I= , PAR= are the keywords.

2. A keyword which selects the type of element in DRAM. This type of keyword is called a generic keyword.

For Example:

```
FIELD/1,DAMPER,I=2,J=3,PAR=5
```

where the damper is a generic keyword.

3.2 ID OF STATEMENTS:

The identification number of a statement identifies the particular input data statement. The same type of statement can be used repeatedly with different ID numbers. The identification number must be an integer and must be in the range 0<ID<9999. The ID number must be within five columns following the slash (/).

For Example:

FIELD/12,.......

where 12 is the identification number of the FIELD statement.

3.3 PARAMETERS:

Input values must be assigned to certain statement types via parameters. Ten values can be passed via a parameter statement. Each value must be separated by a comma. Blanks may be inserted anywhere in the parameter entry except within numeric values.

For Example:

PAR=PAR1,PAR2,.......,PARN

where PAR1=numerical value1,PAR2=numerical value2,...... PARN=numerical valueN.

The parameter values are always assumed to be in radians. However, the parameter values can be assigned in degrees by using keywords DEG or DINV.

For Example:

PAR=(DEG=PAR1,DEG=PAR2,DINV=PAR3,......)

where DEG corresponds to degrees and DINV corresponds to 1/degrees (inverse of DEG).

3.4 PART:

DRAM assumes parts are rigid and inextensible. Parts may or may not have mass. A part may be motionless. A motionless part is referred to as a ground part. A ground part has a fixed coordinate system which is called the GROUND REFERENCE AXIS (FRAME). Velocities (angular and translational) of the ground part are considered zero since the ground part is fixed. The moving part also has its own coordinate system which is called the LOCAL PART REFERENCE AXIS (FRAME). Motions of the moving parts are measured with respect to the ground reference axis and hence the angular velocities of parts are absolute.

If the system simulated is kinematic, the mass and mass moment of inertia of the mechanical system can be eliminated from the input data. However, the mass and mass moment of inertia can not be eliminated from the input data if the reaction forces at the contacts are required. In absence of the mass and mass moment inertia, DRAM will still calculate the reaction forces at the contact, but the calculated values of the reaction forces will not be correct. The mass and mass moment of inertia do not have any effect on the calculation of the displacement, velocity and acceleration for a kinematic system.

3.5 MARKERS:

Markers are used to define the geometry of contact between parts, to define the points of action of force fields, to denote the center of mass and to designate the geometry of the part including orientation. Markers can be located anywhere on the part and can be superimposed.

3.6 CONTACTS:

DRAM accommodates two types of contacts, namely, rotational contacts and translational contacts.

The two markers of the rotational contact (eg. rotational contact between the slider and its connecting rod) must be aligned (to bring together as a rotational contact) as either a POINT or a GMARKER. The two markers of the translational contact (eg. translational slider contact with respect to its fixed ground contact) must be aligned by the two GMARKERS only. The POINT and GMARKER are defined in the next chapter. Refer to chapter 7 for an example.

3.7 GENERATORS:

The function of the generator is to generate a desired motion. The generated motion of the system can be rotational or translational. The slider crank mechanism is a good example of the rotational and translational generator. The rotational generator provides the crank with a prescribed rotation, whereas in the same mechanism, the translational generator can be used when the slider has a prescribed translation.

3.8 FIELDS:

A FIELD is an applied force exerted between a pair of markers, each fixed in a different part. If a field is translational, it acts along the line between marker I and marker J and is positive if the markers are repelled, and negative if the markers are attracted. Similarly, if a field is rotational, the field is positive if it increases the relative angle, and negative if it decreases it.

3.9 SYSTEM:

The SYSTEM statement controls the execution of the DRAM program. It has control over the integration, begin value, integration time step, relative errors and the gravitational constant etc.

3.10 OUTPUT:

The OUTPUT statement controls the cycle time and formats the output request. It also saves the graphics and request files for DRAM's POSTPROCESSOR. The postprocessor is used for computer-aided-design, and provides graphic output.

3.11 REQUESTS:

The REQUEST statement produces the specific output of interest. The output request can be of three types: (1) DRAM's standard type (2) Output by RSUB subroutine (3) Output by User's input expression.

Output of displacement, velocity and acceleration is measured by considering the marker I relative to the marker J. Similarly, the output of force is tabulated as the force exerted on the marker I by the marker J.

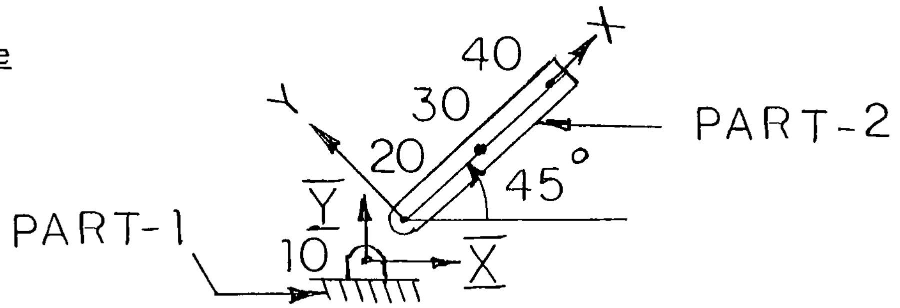
The following types of markers are allowed in the force request.

1. For a translational force, markers I and J must be either a POINT or a GMARKER.
2. For a rotational force (torque), markers I and J must be either a DIRECTION marker or a GMARKER. The DIRECTION marker is defined in the next chapter.

3.12 COORDINATE SYSTEMS:

A mechanical system must be described by means of a coordinate axis system. There are two types of coordinate axis systems, namely the local part reference axis (frame) system and the ground reference axis (frame) system. Each part is assumed to have a right hand reference axis system called the local part reference axis system. The positions of all markers of the part are described by the local part reference axis system. The fixed part of the mechanical system is described by the ground reference axis system. In this coordinate axis system, the direction of the X axis and Y axis must not be changed. That is, the positive X axis direction must face toward the right and the positive Y axis direction must face upward. DRAM follows this convention for any kind of problem.

For Example



$\overline{X}$ $\overline{Y}$ - Ground reference axis (frame).

x y - Local part reference axis (frame).

Length of slender rod = 2 inch.

FIG. 3.1 : SLENDER ROD

Two part statements can be written as follows:

```
PART/1,GROUND
MARKER/10,POINT,PART=1,X=0,Y=0
```

Here X=0, Y=0 are the coordinates of the ground reference axis (frame) system. Marker 10 is located at the origin of the ground reference axis (frame) system.

```
PART/2 MASS=0,CM=30,INERTIA=0,ANGLE=45
MARKER/20,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/30,POINT,PART=2,X=1,Y=0
MARKER/40,POINT,PART=2,X=2,Y=0
```

Part 2 makes an angle of 45 degrees with respect to the ground reference axis (frame) system (positive in counterclockwise direction). The values of X and Y are local coordinates and describe the position of markers 20,30,40 in part 2. Markers 20,30,40 do not make an angle with the local part reference axis (frame) system. Hence ANGLE=0.

CHAPTER 4 : DESCRIPTION OF INPUT STATEMENTS

All input data statements of DRAM are described in this chapter in the order in which they usually occur in a program. Sample examples are given whenever needed. It is important to note that the keywords of a statement must be separated from others by a comma. A reader should refer to chapter 7 while reading this chapter.

4.1 PART STATEMENT:

The part statement has been classified into two types for simplicity. The first type of PART deals with a FIXED GROUND PART whereas the second type of PART deals with all MOVING PARTS. These PART statements are defined as follows.

<u>FIXED GROUND PART:</u>

PART/ID,GROUND

<u>MOVING PARTS:</u>

PART/ID,MASS=VALUE,CM=VALUE,INERTIA=VALUE,ANGLE=VALUE

/RANGLE=VALUE,DANGLE=VALUE/DEGDANGLE=VALUE,EXACT

Note: A slash (/) mark between the two keywords describes a possible option except the slash of PART/ID.

<u>For example:</u>

ANGLE=VALUE/RANGLE=Value means the value of the angle can be used either in degrees or in radians depending on the requirement of the particular problem.

KEYWORD DEFINITIONS:

<u>ID:</u>

Identification number which identifies the particular part of the system.

<u>GROUND:</u>

Describes the ground part of the system. There must be one and only one ground part in the system.

<u>MASS:</u>

Describes the mass of the part. Mass values must be consistent with the system of units in use. DRAM will automatically divide the value of mass by the gravitational constant/factor g_c. Since the value of the gravitational constant/factor g_c in the SI system is 1, the assigned value of mass must be a consistent mass value. In the FPS system if a mass is in lbm, the value of the gravitational factor will be 32.2 (if all units are in feet) or 386.088 (if all units are in inches). If the mass is in slug then the value of gravitational constant/factor becomes 1. Refer to section 10.2 of chapter 10 for additional details on units.

<u>CM:</u>

Describes the location of the center of mass of the part. The value to be assigned for the CM must be a marker ID of the center of mass of the part.

INERTIA:

Describes the mass moment of inertia of the part at the center of mass. However, the value to be assigned for the mass moment of inertia must be consistent with the gravitational constant. DRAM will divide the value of mass moment of inertia by the gravitational constant automatically. See the mass keyword definition for the additional details.

ANGLE:

Describes the initial position of the local part reference axis (frame) of the part with respect to the ground reference axis (frame) of the ground part. The angle is measured counterclockwise in DEGREES from the x-axis of the ground reference axis (frame) to the x-axis of the local part reference axis (frame). Defaults to 999999.0 which signals DRAM that no value has been input, not even zero.

RANGLE:

Describes another possible option for the initial angle. With this option, the value of angle can be input in RADIANS.
The rest of this description is the same as ANGLE.

DANGLE:

Describes the initial angular velocity of the part with respect to ground in RADIANS/UNIT-TIME. The counterclockwise direction is positive whereas the clockwise direction is negative.

DEGDANGLE:

Describes another possible option for the initial angular velocity. With this option, the value of angular velocity can be input in DEGREES/UNIT-TIME.

EXACT:

If this option is selected, the initial values of ANGLE/RANGLE and DANGLE/DEGDANGLE will be held constant by DRAM. If iteration on the problem coordinates is required to determine consistent initial conditions, other coordinates will be varied.

For Example:

```
PART/1,GROUND
PART/2,MASS=20,CM=3,INERTIA=0.01,ANGLE=0,DEGDANGLE=300
,EXACT
```

PART 1 is a fixed ground part. PART 2 has a mass of 20 lbm and is subjected to a rotation with an initial angular velocity of 300 degrees/sec (ccw). The initial inclination of PART 2 with respect to the ground PART 1 is zero. The values of ANGLE and DEGDANGLE will be considered EXACT. This means, DRAM will keep the initial values of angle and angular velocity constant. The other coordinates such as length etc. will be varied, if it is required to determine consistent initial conditions (angles and angular velocities).

4.2 MARKER STATEMENT:

MARKER/ID,POINT/DIRECTION/GMARKER,PART=VALUE,X=VALUE ,Y=VALUE,ANGLE=VALUE/RANGLE=VALUE

Note: A slash (/) mark between the two keywords describes a possible option except the MARKER/ID.

KEYWORD DEFINITIONS:

ID:

Identification number which identifies the particular marker in the part.

POINT:

It describes a marker as a point only. If the POINT, DIRECTION and GMARKER are all omitted and no value of ANGLE or RANGLE is assigned, the marker is established by default as a POINT. The marker is assumed to be floating if no value of x and y are assigned. Floating markers need to be used when the two impact points of two impacting bodies are to be described in the absence of the co-ordinates X and Y.

DIRECTION:

Marker is a unit vector only.

GMARKER:

It describes a marker as both a point and a unit vector. A unit vector lies along a straight line of the local axis. If POINT, DIRECTION and GMARKER are all omitted but a value (even zero) is assigned for ANGLE or RANGLE, the marker is established by default as a GMARKER. That is, in absence of the GMARKER keyword in the statement, the marker will be considered as a GMARKER if the statement is assigned with ANGLE or RANGLE value including the zero value.

The GMARKER is used in the following instances:

1. Rotational/ Translational contacts.
2. Torsional vibrating spring.
3. Field statements where subroutines are called.
4. Special requests (requests made through the RSUB subroutine).

PART:

Part identification number identifies the part that this marker is fixed to, Defaults to part identification number (value) of the most recent preceding PART/ID statement.

X,Y:

The rectangular coordinates of a POINT or GMARKER with respect to the origin of the local part reference axis (frame).

ANGLE:

Angle of the unit vector of a DIRECTION or GMARKER with respect to the X axis of the local part reference axis . It is measured positive in the counterclockwise direction, and is measured in DEGREES.

RANGLE:

Describes another possible option for the angle. With this option, the value of angle can be input in radians and otherwise is the same as ANGLE.

For Example:

MARKER/2,GMARKER,PART=1,X=2,Y=1,RANGLE=0.78539816

Marker 2 is a GMARKER and is a located at a distance x=2 inches ,y=1 inch from the origin of the local part reference axis (frame) on part 1. Marker 2 makes 0.78539816 radian angle with respect to the X axis of the local part reference system.

4.3 ROTATION STATEMENT:

```
ROTATION/ID,I=VALUE,J=VALUE
```

KEYWORD DEFINITIONS:

<u>ID:</u>

Rotation identification number.

<u>I:</u>

Identification number of marker I on part K, where part K is a part of the mechanical system.

<u>J:</u>

Identification number of marker J on part L, where part L is a another part of the mechanical system.

<u>For Example:</u>

```
ROTATION/1,I=10,J=20
```

Part 2 and part 3 have the markers I=10, J=20 respectively. These two markers have rotational motion which is identified by rotational ID =1. This statement can also be written as follows:

```
ROTATION/1,10,20
```

The first value after the ID number will be assigned to marker I and the next value after that will be assigned to marker J. In short, the values will be assigned as I=10, J=20, where 10 and 20 are the markers connected rotationally.

4.4 TRANSLATION STATEMENT:

TRANSLATION/ID,I=VALUE,J=VALUE,TRANS=VALUE
,DTRANS=VALUE,EXACT

KEYWORD DEFINITIONS:

<u>ID:</u>

Translational identification number.

<u>I:</u>

Identification number of marker I on part K, where part K is a part of the mechanical system.

<u>J:</u>

Identification number of marker J on part L, where part L is a another part of the mechanical system.

<u>TRANS:</u>

Initial translational displacement of marker I with respect to marker J. The displacement of marker I with respective to marker J is considered positive in direction of the unit vectors of markers I and J.

<u>DTRANS:</u>

Initial translational velocity of marker I with respect to marker J.

<u>EXACT:</u>

The initial values of TRANS and DTRANS will be held constant by DRAM. If iteration on the problem coordinates is required to determine consistent initial conditions, other coordinates will be varied.

For Example:

```
TRANSLATION/1,I=100,J=200,TRANS=2,DTRANS=0,EXACT
```

Part 2 and part 3 have markers I=100 and J=200 respectively. The initial displacement of marker I with respect to marker J is 2 inches measured positive in the positive X direction. The intial velocity of marker I with to marker J is considered as zero. EXACT will hold the values of TRANS and DTRANS constant.

4.5 GENERATOR STATEMENT:

GENERATOR/ID,ROTATIONAL/TRANSLATIONAL,ON=VALUE

,FROM=VALUE,CONSTANT VELOCITY/HARMONIC/INPUT

,PAR=PAR1,PAR2.........,PARN

Note: A slash (/) mark among the keywords describes a possible option except the slash of GENERATOR/ID.

KEYWORD DEFINITIONS:

ID:

Generator identification number.

ROTATIONAL:

Generator action is rotational.

TRANSLATIONAL:

Generator action is translational.

ON:

Identification number of the part where the generator is generating a rotational or translational motion (part number of the part on which the generator acts).

FROM:

Part identification number from which the generator acts. Used when the generator is a ROTATIONAL generator. Defaults to ground part.

CONSTANT VELOCITY:

Generator moves with the constant velocity.

The parameters to be used for the velocity and displacement are as follows:

1. Constant velocity.

   For rotational motion, the value of the angular velocity would be the angular velocity of the part specified in "ON" minus the angular velocity of the "FROM" part. It is measured in rad/unit-time and is positive in the counterclockwise direction.

   For translational motion, the velocity of translation is the same as DTRANS. It acts on the translational contact specified in "ON". DTRANS is positive in the positive X direction.

2. Initial displacement.

   For the rotational motion, the value of initial displacement would be the difference between the angle of the part identified by "ON" and the angle of the part identified by "FORM".

   For translational motion, the value of initial displacement is the same as TRANS. TRANS acts on the translational contact specified in "ON".

The values of 1 and 2 must be input in the parameters (PAR) in the order in which they are explained above. That is, the 1st and 2nd parameter values are the constant velocity value and initial displacement value respectively and can not be interchanged.

<u>HARMONIC:</u>

Generator displacement equals $A*\sin(wt-\phi)+B$

Where A = Amplitude of displacement

w = Frequency (radians/unit time)

ϕ = Phase angle (radians)

B = average value

The values of A,W,ϕ, and B must be input through the parameter statement in the order in which they are explained.

INPUT:

Describes that the subroutine "GENSUB" has to be linked to DRAM.

PAR:

Ten parameter values are allowed through the parameter. Whenever the angular units are involved, DRAM will assume all units in radians. However, the angular units can be input in degrees by using DEGPAR=.... statement. The angular units can also be input in 1/radians by using DINVAR=.... statement (inverse form of DEGPAR). Alternatively, degrees can be input by suffixing the numerical value by 'D'.

For Example:

```
GENERATOR/2,ROTATIONAL,ON=2,FROM=1,CONSTANT VELOCITY
,DEGPAR=3000,PAR=45.0D
```

A rotational generator with its ID=2 is acting on part 2 from part 1 (ground part). The constant angular velocity of part 2 is 3000 degrees/sec. Initially, the local part reference axis (frame) of part 2 makes an angle of 45 degrees with respect to the ground reference axis (frame) of part 1.

4.6 FIELD STATEMENT:

A field is an applied force exerted between a pair of markers each fixed in a different part of the system. Inertial forces and gravitational forces are developed automatically by DRAM.

FIELD/ID,ROTATIONAL/TRANSLATIONAL,SPRING/PULLEY BELT/
HARMONIC/DAMPER/INPUT/WALL/CONSTANT/DEPENDENT/
FRICTION/USER,I=VALUEi,J=VALUEj/JF=VALUEjf,KF=VALUEkf
,K=VALUEk,L=VALUEl,M=VALUEm,ANGLE=VALUEa/
RANGLE=VALUEr,PAR=PAR1,PAR2,......PAR10,F=EXPRESSION

Note: A slash (/) mark among the keywords describes a possible option except the slash of FIELD/ID.

KEYWORD DEFINITIONS:

ID:

Field identification number.

ROTATIONAL:

Indicates that the field is rotational.

TRANSLATIONAL:

Indicates a translational field (the translational field is created by an applied translational force).

SPRING:

Linear spring (translational or rotational).

PULLEY BELT:

Describes pulley belt (rotational only).

HARMONIC:

Harmonic forcing function.

DAMPER:

Viscous damping force.

INPUT:

Indicates that the function subprogram 'USUB' has to be linked to DRAM.

WALL:

Indicates that the force to be considered is a wall force.

CONSTANT:

A force or torque of constant magnitude.

DEPENDENT:

A force is either dependent in magnitude (unknown magnitude), with direction defined by subsequent entries, or it is entirely dependent, where both the magnitude and direction are unknown.

FRICTION:

Coulomb friction.

USER:

A user defined force.

I:

Identification number of marker I.

J:

Identification number of marker J.

JF:

Marker identification which is used to determine the angle of an action force only. The action force is that force which acts on the body (marker). JF is used for specifying the vector relative to which the angle of the field direction is measured (J direction).

KF:

Marker identification which is used to determine the angle of action force only. KF is used for specifying the vector relative to which the angle of the field direction is measured (K direction).

K,L,M:

Used with I and J to determine a floating marker coordinate system. The coodinates x and y of these markers are not specified, but they will be calculated by DRAM automatically.

ANGLE:

Angle, in degrees, made by an action force. Also used in the static equilibrium configuration.

RANGLE:

Describes another possible option for the angle. With this option, the value of angle can be input in radians. The other description is the same as ANGLE.

F:

User force function. The force function is a force expression which can be directly written into the input data coding routine instead of writting the seperate subprogram.

PAR:

Describes parameter list. The angular units are assumed in radians. However, the angular units can be input in DEGREES by using DEGPAR=..... or DINVPAR=..... DINVPAR is the inverse of DEGPAR (1/degrees). The values of parameter must be input in the order in which they are listed.

The FIELD PARAMETER LIST for different options is given below:

OPTIONS:

SPRING:*

1. Stiffness (spring constant). The sign of this entry is positive due to the fact that the direction of the force exerted by a spring on a system is reversed by DRAM to the displacement of the marker on which the force acts.

2. Length of spring with no load. For torsional or rotational spring, this is an angle in radians measured with respect to the angular displacement of the spring terminals at no load.

PULLEY BELT:*

1. Stiffness of a unit length of one span of the belt.

2. Effective radius of pulley I (core radius of pulley I).

3. Effective radius of pulley J (core radius of pulley J).

4. The value of angle to be assigned is the initial angle of pulley I, minus the initial angle of pulley J. The pulley angle is measured with respect to the pulley orientation corresponding to the zero tension in both belt spans. The value of this angle turns out to be zero.

5. Enter integer 0 if belt spans are not crossed; 1 if belt spans are crossed. (Note that the location of the pulley centers is assumed by DRAM to be the location of markers I and J referenced in the general field input).

HARMONIC FORCE:*

Harmonic force= (F=A SIN (Wt-ϕ) + B)

where:

1. A = Amplitude.
2. W = Frequency (radians/unit time).
3. ϕ = Phase angle (radians).
4. B = Average value. A force F which is simply constant can be input by entering A as zero and

---

* The values of 1,2,3....etc must be input through the parameter statement in the order in which they are descibed above.

entering B as the constant value.

5.&6. = Identification numbers of markers M and N used to determine the direction of force F. Entries 5 and 6 will correspond to markers M and N respectively. There are four circumstances to consider here:

A. If the field is rotational, the positive direction is always +k and entries in 5 and 6 will be ignored. +k is considered to be positive in the z-direction of the x-y-z coordinate system.

<u>For Example:</u>

FIELD/1,ROTATIONAL,HARMONIC,I=10,J=15
,(PAR=VAL1,VAL2,VAL3,VAL4,VAL5,VAL6)
,F=A*SIN(W*T-φ)+B

The values VAL5 and VAL6 are provided. However these values will be ignored due to the rotational field.

B. For a translational field, if both entries 5 and 6 are omitted, F is assumed codirected with a vector to marker I from marker J.

<u>For Example:</u>

FIELD/1,TRANSLATIONAL,HARMONIC,I=12,J=13
,(PAR=VAL1,VAL2,VAL3,VAL4),F=A*SIN(W*T-φ)+B

The values VAL5 and VAL6 are omitted.

C. For translational field, if only one of the entries

---

* The values of 1,2,....etc must be input through the parameter statement in the order in which they are described above.

5 and 6 is omitted, the other entry must be either a direction or gmarker type marker. F is then assumed codirected with the unit vector of the marker in the local coordinate system.

For Example:

```
FIELD/2,TRANSLATIONAL,HARMONIC,I=10,J=15
,(PAR=VAL1,VAL2,VAL3,VAL4,VAL5),F=A*SIN(W*T-ϕ)+B
```

The value VAL6 is omitted.

D. For a translational field, if both entries 5 and 6 are provided, markers M and N must both be either point or gmarker type markers. F is then assumed codirected with a vector to marker M from marker N.

For Example:

```
FIELD/1,TRANSLATIONAL,HARMONIC,I=10,J=15
,(PAR=VAL1,VAL2,VAL3,VAL4,VAL5,VAL6),F=A*SIN(W*T-ϕ)+B
```

The values VAL5 and VAL6 are provided.

VISCOUS DAMPING:*

The force equation for viscous damping: F=-CX or F= CX

1. Damping coefficient "C".

WALL FORCE:*

The expression used in DRAM for impact force is F=k(a-d)**3/2 u(a-d)

where u(a-d)=0 for d>a and u(a-d)=1 for d<=a. a= Sum of

---

* The values of 1,2,....etc must be input through the parameter statement in the order in which they are described above.

the radii of the impacting surfaces after impact. Formulas for k of various geometries are available in Roark, R. j., "Formulas for Stress and Strain", 4th Edition, McGraw-Hill, 1965, Table XIV, pg 319. d= The actual distance between markers I and J at any time. d > a for no impact and d <= a during impact. For the additional information refer to the "DRAM users guide" pg 66.

The following are parameter values to be used in the parameter statement of the wall force.

1. Sum of the radii of the impacting surfaces, a
2. Effective surface stiffness, k.
3. Coefficient of restitution, e.

<u>For Example:</u>

```
FIELD/1,TRANSLATIONAL,WALL,I=10,J=20,PAR=VAL1,VAL2,VAL3
,F=K*(A-D)**3/2
```

where VAL1= sum of radii of the impacting surface.

VAL2= effective sueface stiffness.

VAL3= coefficient of restitution.

<u>CONSTANT:</u>

1. Magnitude of force or torque.

<u>DEPENDENT:</u>

A dependent field type. It describes dependency of the force on other entries described in the FIELD statement. A force is either dependent in magnitude (unknown

---

* The values of 1,2,....etc must be input through the parameter statement in the order in which they are described above.

magnitude), with direction defined by subsequent entries; or it is entirely dependent, with both the magnitude and direction are unknown. If one or more dependent field types are included, DRAM will automatically run in a static equilibrium balancing mode, in an attempt to determine the dependent magnitudes and or component values.

<u>For Example:</u>

FIELD/1,TRANSLATIONAL,DEPENDENT,I=10,J=15,F=FO*SIN(W*T)

<u>FRICTION:*</u>

The friction Equation: F= u*N where N is the normal force.

1. Coefficient of friction ,u.

2. Radius of joint, r (r=1 for translations). This value is required because rotational joints can impart a torque and the radius of the joint is needed to calculate this torque.

3. Allowable error in predictor/corrector. The friction force is in itself a function of another force (the normal force). Because of this, an iterative procedure is required to accurately calculate F. This error is typically .01-.001.

4. Velocity for friction to reach a limiting value. Near zero velocity the friction force is nearly discontinuous, hence a velocity is required to

---

* The values of 1,2,....etc must be input through the parameter statement in the order in which they are described above.

eliminate this problem. Typically this velocity should be about 5%-10% of the actual velocity.

For Example:

FIELD/1,TRANSLATIONAL,FRICTION,I=10,J=15

,PAR=(VAL1,VAL2,VAL3,VAL4),F=U*N

where VAL1= coefficient of friction.

VAL2= radius of joint.

VAL3= allowable error.

VAL4= velocity for friction.

USER:

Since it indicates the user force function, there are no parameters for user.

In general, a FIELD statement can be written as :

FIELD/1,TRANSLATIONAL,CONSTANT,I=10,ANGLE=180,PA=50

A constant translational force of 50 pound is applied on marker 10 through the field (ID=1) statement. The force makes an angle of 180 degrees with the horizontal axis.

Note: Other options, in addition to the TRANSLATION and CONSTANT, can be used in this FIELD/1 statement as well.

4.7 SYSTEM STATEMENT:

SYSTEM/BEGIN=VALUE,IGRAV=VALUE,JGRAV=VALUE,KGRAV=VALUE
,GC=VALUE,ERR=VALUE,TS=VALUE,IRAT=VALUE,STIFF,IC=VALUE
,ACC=VALUE,EQUILIBRIUM,EQERR=VALUE

KEYWORD DEFINITIONS:

BEGIN:

Initial value of time. At this time the specified initial conditions apply and the program starts. Defaults to zero. It is a good practice to start the problem with initial time t=0. Hence, use the default.

IGRAV,JGRAV,KGRAV:

I, J and K components of the gravitational acceleration vector, used to describe the tilt of the plane of motion with respect to the direction of gravity. All default to zero. The directions of I, J, K components of the gravitational acceleration are positive in the positive directions of X, Y, Z axes respectively.

GC:

Gravitational constant/factor. The units of the gravitational constant must be consistent with the units assumed elsewhere the input. The gravitational constant depends on the system, either SI or FPS, to be used. Defaults to 1.0 . Refer to chapter 10.

ERR:

Maximum allowable relative error per integration step for the integration routine. Defaults to 1.E-04. The Adams-Moulton routine is used for the integration. The fourth-order Adams-Bashforth and Adams-Moulton formula started with the fourth-order Runge Kutta method is referred to as the Adams-Moulton method. For more details refer to Ward Cheney, David Kinchaid (text) P. 404-409 .

TS:

Maximum allowed integration time step. Defaults to one output step size. Output step size is a time interval at which output values are printed.

IRAT:

Initial integration time step is IRAT x TS in size. Default: Initial time step equals (.001)x TS. and IRAT=0.001.

STIFF:

Replace Adams-Moulton integration with Gear Algorithm routine (appropriate for systems combining motions of widely separated frequency where the high frequency motion decays rapidly). Defaults to Adams-Moulton routine.

EQUILIBRIUM:

Describes a static equilibrium configuration solution.

EQERR:

Used to specify an error criterion for a static equilibrium solution. The static equilibrium process terminates when the sum of the accelerations squared of all the parts is less than or equal to EQERR. If not entered, a value will be calculated based on system parameters.

IC=n:

Controls the integration to determine the initial conditions consistent with the mechanical constraints. Defaults to IC=1.

If n=0, then no iteration. Integrate directly from specified initial conditions.

If n=1, then iterate to determine the consistent initial conditions within the number of digits of accuracy specified by ACC. If no convergence is achieved after 25 iterations, DRAM writes a message and attempts to run anyway.

If n=2, then a trace of the iterations is written. The rest of this description is the same as IC=1.

ACC:

Specifies the number of significant digits of accuracy to which the initial conditions are to be calculated. The maximum significant digit accuracy is up to 17 digits. Defaults to 15.

For Example:

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-04,IC=1

The system has a gravitational constant (GC)= 386.088 lbm-in/lbf-sq.sec. and is positive in the downward direction. The direction of the component J of the gravitational acceleration is assumed positive upward. Hence the value of JGRAV is suffixed with the minus sign. The maximum allowed relative error is 1.0E-04 and the initial condition is 1.

The system statement does have some additional options which may not be needed. These options are DUMP=n, EDUMP, HALT=n, TRACE=n. These deal with APLAX, MPLEX, TOPOLOGY tables and integration steps. Refer to the Mechanical Dynamic Inc.'s user guide (page 78).

4.8 OUTPUT STATEMENT:

```
OUTPUT/BEGIN=VALUE,END=VALUE,STEPS=VALUE,FSTEP,VSTEP
,RANGLE,REVANGLE,DREVANGLE,OSFORMAT/TRFORMAT,TELETYPE/
PRINTER,NOPLOT,XYPLOT=n/BIGPLOT=n,SCALE=VALUE
,XCENT=VALUE,YCENT=VALUE,ANGLE=VALUE,BASEMARKER=n,GRID/
NOGRID,RESTART,REVIEW,SAVE,XSCALE=VALUE,YSCALE=VALUE
,GRSAVE,SAVEINT,SAVEOUT
```

Note: A slash (/) mark between the keywords describes a possible option except the slash of OUTPUT/BEGIN.

KEYWORD DEFINITIONS:

<u>BEGIN:</u>

Output begins at this time. Defaults to BEGIN with the time assigned by the SYSTEM statement. (The SYSTEM statement also has a "BEGIN=value" option.)

<u>END:</u>

Both the output and the simulation end at this time. END must equal or exceed BEGIN. Defaults to zero.

<u>STEPS:</u>

Output will be reported at the beginning time t equal to the assigned value of BEGIN statement and finishing at time t equal to the assigned value of END statement. If STEPS value is omitted, the default is 50 steps.

<u>FSTEP:</u>

The output specified in STEPS=VALUE will be equally spaced, within an error limit of +- 1% on step size. If not specified, the default is to output in FSTEP.

VSTEP:

If this option is used, the output becomes irregularly spaced (that is the step size does not remain fixed). Default is to a fixed output step. Fewer integration steps are required when VSTEP is specified.

RANGLE:

The units of all output angular displacements will be in radians. If not specified the default is to output in degrees.

REVANGLE:

The units of all output angular velocities are in revolutions per unit time. Defaults to output in radians per unit time.

DREVANGLE:

The units of all output angular accelerations are in revolutions per unit time squared. Defaults to output in radians per unit time squared.

OSFORMAT:

All requests for displacement, velocity and accleration are written together at every time step (interval) of output. Defaults to TRFORMAT.

TRFORMAT:

Output of each request is printed separately with the normalized plot. If not specified, the default is to TRFORMAT.

TELETYPE:

Permits a plot of the normalized plot of each output request after printing all output values of each output request (minimum 70 columns). That is, the normalized plot will be printed below the output values of each request instead of printing to the right hand side of output values. Defaults to side by side format.

PRINTER:

Causes adjacent strip-chart (normalized plot) plus tabulated output of request data on the line printer. Defaults to PRINTER.

NOPLOT:

No strip-chart (normalized) output is printed.

XYPLOT=n:

Produces a n+1 printer plot. It allows the user to increase the time step size for the plotting of a normalized plot. The plotting begins at time equal to BEGIN and continues for n equally spaced values (time values) until time equal to the END value.

BIGPLOT=n:

Produces two page printer plot (120 lines). This option is otherwise the same as XYPLOT.

SCALE=VALUE:

The printer plot schematic will be produced within a rectangular 'frame' 8 1/4 x 8 inches in size. VALUE is the length dimension, measured relative to the actual mechanical system (length), which corresponds to 8 1/4 inches on the printer plot drawing. For example: SCALE=.5 This will reduce the actual length of the mechanical system by half.

XCENT=VALUE, YCENT=VALUE:

XCENT and YCENT are the horizontal and vertical coordinates of the center of the axis (frame) of the printer plot drawing, measured relative to the origin of ground reference axis (frame) of the mechanical system. The length units used are those of the actual mechanical system. The axis (frame) of the actual mechanical system is is oriented to align with the horizontal and vertical directions of the system ground reference axis (frame). For example: XCENT=0.25,YCENT=0.25 The actual size on the printer will be reduced by 0.25 on the both X and Y axes.

ANGLE=VALUE:

Angle at which the Tektronix plot is generated with respect to the horizontal axis of the screen. Angle is measured in counterclockwise direction and its value is in degrees. Defaults to zero.

BASEMARKER=n:

Specifies a marker which will be used as a basemarker in the Tektronix plots. Defaults to a marker on the ground.

GRID:

Generates a grid on the printer plots (XYPLOT). Defaults to GRID.

NOGRID:

Does not generate a grid on the printer plots (XYPLOT). Defaults to GRID.

SAVE:

Dumps all the information necessary to restart a job onto the file specified on FORTRAN unit 10. FORTRAN unit 10 is reserved for the save file. By using this SAVE option on the output card, a user can store the results of a simulation and restart the job in a later session at an arbitrary time.

RESTART:

Values necessary to restart a job from a SAVE file is read from FORTRAN unit 11. FORTRAN 11 is reserved for the restart file. The job can be restarted at any arbitrary time by specifying the time in the keyword BEGIN of the system statement. During RESTART the only corrections which can be made to the data are additions, deletions, or changes in the REQUEST, OUTPUT, and/or SYSTEM cards. However, the system geometry must not change. The restart time must be within the range of the initial and final times in the save file. Defaults to NO RESTART.

RVIEW:

Generates the Tektronix plots with respect to the k axis. That is, the plot is flipped around so that it appears that a user is viewing the plot from behind the screen.

XSCALE=VALUE:

Specifies the x-axis scale to be used in generating the Tektronix plots. VALUE is the length dimension, measured with respect to the actual mechanical system, which corresponds to 7-inch x-axis of the screen.

YSCALE=VALUE:

Relates the y-axis values of the mechanical system with the 5 inch long y-axis of the screen.

GRSAVE:

Saves the GRAPHICS of mechanical system for DRAM'S GRAPHICS Post-processor.

SAVEINT:

Saves requests information for the plotting of output graphs at every integration step.

SAVEOUT:

Saves requests information for subsequent post-processing at every output step.

For Example:

OUTPUT/END=0.1,STEPS=25,NOPLOT,RANGLE,SAVEINT,GRSAVE

This output statement describes that the system has 25 time steps with BEGIN time=0 (default value of time) and END time=0.1 sec. All output values will be in radians. Output will not print the normalized plot (NOPLOT), but the graphics (GRSAVE) and request (SAVEINT) files will be saved for the post-processor.

4.9 REQUEST STATEMENT:

REQUEST/ID,DISPLACEMENT/VELOCITY/ACCELERATION/FORCE/
USER/RSUB/MINMAX,I=VALUEi,J=VALUEj,ALL,REC
,R=EXPRESSION,PAR=PAR1,PAR2,......,PAR10
,TITLE=ALPHANUMERIC TITLE,:COMMENT

Note: A slash (/) mark between the keywords describes a possible option except the slash of REQUEST/ID. The option USER indicates the USUB subroutine is to be linked to DRAM.

KEYWORD DEFINITIONS:

DISPLACEMENT (DIS):

Displacement of marker I with respect to marker J.

VELOCITY (VEL):

Velocity of marker I with respect to marker J.

ACCELERATION (ACC):

Acceleration of marker I with respect to marker J.

FORCE:

Force exerted on marker I by marker J.

USER:

Used to denote a user specified request.

RSUB:

A user defined request subroutine.

MINMAX ALL:

MINMAX produces a table of the minimum and maximum values occurred. If ALL is used, values are determined at each successful integration step. Otherwise, values are determined at each output step.

I=VALUEi:

Identification number of marker I.

J=VALUEj:

Identification number of marker J.

REC:

Output is in the rectangular coordinate system. Defaults to polar coordinate system.

R=:

Used to specify a user request.

PAR:

Parameter list. Used to pass values to the RSUB subroutine. A maximum of 10 values can be passed.

TITLE:

A 48 character or less alphanumeric tittle used in the RSUB type of request. TITLE is delimited at an occurence of a comma. TITLE can not be continued on a second line/card.

":"

All characters following the : (colon) will be printed at top of the page on which this request is printed.

For Example:

REQUEST/1,DISPLACEMENT,I=10,J=20

1 is the request identification number. This request will output the displacement of marker 10 with respect to marker 20.

CHAPTER 5 : SUBPROGRAMS

The subroutine/function subprograms to be used for the coding of input data different from DRAM's standard form have been explained in this chapter. All subroutine/function subprograms must be written in the Fortran IV language. It should be noted that the subroutine/function subprogram must be compiled before linking to DRAM.

The following are the important factors in regard to the implementation of these subprograms.

1. Subroutine/function subprogram name must match with DRAM's standard type. For example: The names GENSUB, USUB and RSUB can not be replaced by any other names.
2. Arguments of the subroutine/function subprogram must be in the order in which they are stated in DRAM's standard type.
3. The names of the argument list can not be different than DRAM uses.
4. DRAM does not allow any additional argument in the subroutine/function subprogram argument list.
5. The subroutine/function subprogram must be written in double precision for RIT's VAX/VMS system.

5.1 GENERATORS AND THE GENERATOR SUBROUTINE "GENSUB":

This subroutine subprogram determines the displacement, velocity and acceleration of a particular part as a function of time. Step changes in velocity with respect to time are not allowed by DRAM. It is important to note that the function which is used in the subroutine must be differentiable. That is, the velocity must be the derivative of the displacement and the acceleration must be the derivative of the velocity. When the GENERATOR statement calls the "GENSUB" subroutine, the GENERATOR statement must contain "INPUT" and "PAR=" keywords. The number of parameters can be transferred to and from are 10. Hence, the GENERATOR statement must look like:

```
GENERATOR/ID,ROTATIONAL/ TRANSLATIONAL,INPUT
,ON=VALUE,PAR=PAR1,PAR2,........,PAR10
```

The generator subroutine GENSUB has the following form:

```
SUBROUTINE GENSUB (TIME,PAR,NGEN,X,DX,D2X)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION PAR(10)
 .
 .
 .
 X=
 DX=
 D2X=
```

```
      RETURN
      END
```

KEYWORD DEFINITIONS:

TIME:

Simulation time.

PAR:

Ten parameters.

NGEN:

Identification number of the generator (same as the ID number of the generator). The NGEN can be used to branch to the appropriate section of the subroutine when more than 1 generator is used in the system.

X:

Is the displacement.

DX:

Is the velocity.

D2X:

Is the acceleration.

For Example:

Refer to the Mechanical Dynamics Inc's user guide (page 74). Also refer example 7.8 of this manual.

5.2 FIELDS AND THE USUB FUNCTION SUBPROGRAM:

Fields with an unusual dependence on the displacement, velocity and acceleration can not be applied to the model of a mechanical system through the standard options of the FIELD statement. In this situation, it is essential to write a FIELD function subprogram called USUB. This subprogram is linked to the FIELD statement by including INPUT as an argument in the FIELD statement.

Note that a field statement must have "INPUT" and "PAR=" keywords in order to use the "USUB" FIELD function subprogram. The maximum number of parameters allowed are 10.

The FIELD statement must have the following form:

```
FIELD/ID,TRANSLATIONAL/ ROTATIONAL,INPUT,I=VALUE
,J=VALUE,PAR=PAR1,PAR2,........,PAR10
```

The field function subprogram is specified by the name USUB. The USUB function subprogram has the following form:

```
FUNCTION USUB (RAD,APAR,PAR,NFIELD)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION APAR (10),PAR(10)
.
.
.
USUB=.......
RETURN
```

END

KEYWORD DEFINITIONS:

RAD:

Distance between markers I and J (always positive).

APAR:

At each integration step DRAM passes the following ten parameter values to the USUB function subprogram.

APAR(1) = Time (in simulation)

APAR(2) = The x component of the displacement of marker I with respect to marker J and is measured in the ground reference axis (frame) system.

APAR(3) = The y component of the displacement of marker I with respect to marker J and is measured in the ground reference axis (frame) system.

APAR(4) = The x component of the velocity of marker I with respect to marker J and is measured in the ground reference axis (frame) system.

APAR(5) = The y component of the velocity of marker I with respect to marker J and is measured in the ground reference axis (frame) system.

APAR(6) = Angle (radians) of marker I and is measured counterclockwise with respect to marker J. No entry, if I or J are point markers.

APAR(7) = Angular velocity (radian/unit time) of marker I, measured counterclockwise with respect to marker J. No entry, if I and J are point markers.

APAR(8) = A characteristic (total) length of the system.

APAR(9)& APAR(10) = Unused.

PAR:

Ten parameters are allowed. The "PAR=" transfers values to the USUB function subprogram.

NFIELD:

Identification number of the field. (same as the ID in the FIELD statement.)

At each integration step, DRAM will receive the calculated value of assigned function from the function subprogram via name USUB and interpret this value as the applied force exerted on marker I by marker J. If the force between markers I and J is repulsive, the sign of USUB is positive; if the force between markers I and J is attractive, the sign of USUB is negative.

For Example:

Refer to the Mechanical Dynamics Inc's user guide (page 59). Also refer example 7.8 of this manual.

5.3 REQUEST AND THE RSUB SUBPROGRAM:

A desired output information can be obtained by DRAM, although it is not in a DRAM's standard form. In order to obtain such output information, it is necessary to write a simple Fortran IV "RSUB" subroutine and link it to DRAM. It is important to note that the subroutine must be compiled first before linking to DRAM.

The REQUEST statement in the input data language program must have the following form:

```
REQUEST/ID,RSUB,I=VALUE,J=VALUE
,TITLE=(UPTO 48 CHARACTERS),PAR=(PAR1,PAR2,...,PAR10)
 ,:COMMENTS
```

KEYWORD DEFINITIONS:

ID:

Request identification number.

RSUB:

Describes the user written request.

PAR:

Parameter list used to pass values to the RSUB subroutine.

TITTLE:

A 48 character or less alphanumeric title.

:COMMENT

A comment which will be printed at the top of the page.

:comment is not required however.

The request subroutine RSUB has the following form:

```
SUBROUTINE RSUB(ID,TIME,PAR,RESULT)
```

where

<u>ID:</u>

Request identification number.

<u>TIME:</u>

Simulation time.

<u>PAR:</u>

A ten or less parameter list used to pass values to the RSUB subroutine.

<u>RESULT:</u>

A three element array which is used to pass request values back to DRAM.

The following things should be kept in the mind while writing a RSUB subroutine.

1. The variables TIME, PAR, and RESULT are double precision.
2. Result is three element long. Hence, the user can pass back to DRAM three values.
3. Result is zeroed out prior to each call of the subroutine.
4. PAR and RESULT must be dimensioned as

```
DIMENSION RESULT(3),PAR(10)
```

5. Subroutine INFO can be called from the RSUB to access the displacement, velocity, acceleration, force data from DRAM.
6. Subroutine INFO can be called any number of times in the RSUB subroutine for a particular request.
7. A three element array must be dimensioned in RSUB [DATA1(3),DATA2(3),.....], if subroutine INFO is called.
8. If INFO is called to access force information, then a REQUEST for that force "must" be specified for the marker pair of interest (the force request must be made in the input data). Otherwise, an error will occur.

The following is the form of the INFO subroutine call.

```
CALL INFO(IASK4,IMRKR,JMRKR,IRLMKR,DATA1,ERRFLG)
```

KEYWORD DEFINITIONS:

<u>IASK4:</u>

Stores the four types of requests. Four request types are 'DISP', 'VEL', 'ACC', 'FORC' (Hollerith constants). where:

"DISP" for displacement.

"VEL" for velocity.

"ACC" for acceleration.

"FORC" for force.

These Hollerith constants can be assigned in the program by using the DATA stetement.

IMRKR:

I marker ID number for displacement, velocity, or acceleration. "Request ID number for a force request."

JMRKR:

J marker ID number for displacement, velocity, or acceleration. "Zero for a force request."

IRLMKR:

Relative reference frame marker. Zero for no reference frame marker.

DATA1:

OUTPUT array of three elements as follows:
For displacement (x,y,theta), for velocity (velx,vely,w), for acceleration (accx,accy,w/dt), for force (fx,fy,fz). All angular values are returned in radians. DATA1(3) stores three element values (x,y,theta of displacement) in a single array. Values of the velocity, acceleration, and force will be stored in DATA2(3), DATA3(3), DATA4(3) respectively (again arrary 3 stands for three element values). DRAM does not accept DATA1(1,1,1).

ERRFLG:

Logical TRUE (flag) for error in subroutine call.

In the RSUB subroutine, ERRFLG should be checked immediately after returning from the call to INFO. If ERRFLG is logical "TRUE", an error occurred in the call INFO argument list and the array DATA1 will be undefined. Possible causes of an error are misspelling of the request type, marker ID numbers not being defined in the DRAM input data for displacement, velocity, or acceleration, or the request ID number for a force request is not defined in the DRAM input data. In order to get force data from the INFO subroutine, the force must be requested in the DRAM input data in a REQUEST statement.

The RSUB subroutine could be in the following form:

```
      SUBROUTINE RSUB(ID,TIME,PAR,RESULT)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION PAR(10),RESULT(3),DATA1(3),DATA2(3)
*   THE NUMBER OF DATA STATEMENTS CAN BE UPTO  DATAn(3).
      DIMENSION ITYPE(4)
      DATA ITYPE/'DISP','VEL','ACC','FORC'/
      LOGICAL ERRFLG
      .
      .
      .
      CALCULATIONS
      .
      .
      .
      IMRKR1=........<=== WRITE I MARKER ID FOR DISPlACEMENT
                          OR VELOCITY OR ACCELERATION OR
                          REQUEST ID FOR FORCE.
      JMRKR1=........<=== WRITE J MARKER ID FOR DISPLACEMENT
```

```
                          OR VELOCITY OR ACCELERATION OR
                          ZERO FOR FORCE.
      IRLMKR1=.......<=== WRITE ID OF REFERENCE FRAME MARKER
                          ZERO FOR NO REFERENCE.
      CALL INFO (ITYPE(N),IMRKR1,JMRKR1,IRLMKR1,DATA1,
     / ERRFLG)
      IF (ERRFLG) GO TO 100
      .
      CALCULATIONS
      .
      CALL INFO (ITYPE(N),IMRKR2,JMRKR2,IRLMKR2,DATA2,
     / ERRFLG)
      IF (ERRFLG) GO TO 100
      .
      CALCULATIONS
      .
      RESULT(1)=......
      RESULT(2)=......
      RESULT(3)=......
      RETURN
100   CONTINUE
      .
      .
      ERROR CONDITION ===> THE CONDITION CAN BE WRITTEN AS
                           FOLLOWS.
      WRITE (6,101)
101    FORMAT(' AN ERROR IN INFO SUBROUTINE ARGUMENT')
      .
```

```
      .
      RETURN
      END
```

If there is only one result value in the subroutine, then DRAM will fill the remaining two results places with zeros on the output.

6.1

GETTING STARTED WITH DRAM ON THE VAX/VMS AT RIT

DRAM software is available on VAXC system only.

GETTING STARTED COMMANDS:-

Logon on the vaxv system.

The screen will display $ sign.

Type 'DRAM' after $ sign.

For Example:

$DRAM then hit <cr> Where <cr> ==>carriage return.

The following message will display on the screen.

"Enter DRAM input-file name (or QUIT)" -------- then hit <cr>.

For Example:

File name- sixbar.drm

Option: The file type [.drm] is optional.

After hitting the carriage return,the following message will display on the screen.

"Enter run-name for output files (<cr>=none)" -------

For example:

Output file name- sixbar (Another name can also be used.)

It is not permissible to type "file type" [.out]. DRAM does, however, create the file type after the execution of the program. After hitting the carriage return, the following message will display on the screen.

"Enter subroutine binary-file name (<cr>=none)"--------

The subroutine binary-file name must be assigned if the subroutine needs to be linked to DRAM. Otherwise hit <cr>. The subroutine binary-file is the subroutine file name. The subroutine must be compiled before linking to DRAM.

For Example:

Subroutine binary-file : sixbar1.for or type only sixbar1 then hit <cr>.

After hitting the carriage return, the next message on the screen will be

"Enter next subroutine binary-file name (<cr>=none)"-------

For Example:

Next subroutine binary-file name: sixbar2.for

This allows to link the next subroutine file name. If there is no subroutine to link, then hit the carriage return. The message on the screen will be

"Do you have your own linked version of DRAM (Y/N)(<cr>=N)" --------

This prompt can be used if and only if, the program needs to run a second time without making any change in the subroutine file. This command saves subroutine linking time. Hence, it is not needed to enter the subroutine binary-file name for every run of the program.

If the answer to this command is : Y <cr>

The screen will display the following message

"Enter name of linked DRAM file" ------- <cr>

For Example:

Name of linked DRAM file : DRAM.EXE

DRAM does not accept any another name. The file type [.exe] is optional.

The next message on the screen will be

"Do you want to run in batch mode ? (Y/N) (<cr>=N)-------

If the answer is YES, it will allow you to do some other work while the program is running. If the answer is NO the message on the screen will be

"Do you want to run in debug mode ?(Y/N) (<cr>=N)"-------

Debugging can be done in this mode by typing Y, or otherwise type <cr>. In the debug mode, the changes in the program can be done.

The last message on the screen will be

'Send output to terminal ? (Y/N) (<cr>=N)"---------

NOTE:- If the output file name is assigned previously, the answer to this message must be NO by typing "N". DRAM does not send output to the terminal when the output file is assigned. Moreover, DRAM ignores both output to the output file and output to the terminal. In other words, it does not create an output file and it does not send output to the terminal. After inputting all of this information, the execution of DRAM begins.......

The execution of DRAM is done in different phases. These phases can be seen during the execution.

After FORTRAN STOP, the following messages will be displayed on the screen.

DRAM output file is :------

DRAM graphics file is :----

DRAM requests file is :----

For Example:

DRAM output file is : sixbar.out

DRAM graphics file is : sixbar.gra

The graphics file will be created,if the graphics request is made in the DRAM input language program.

Otherwise, the message

"No graphic file produced by this run" message will be displayed on the screen.

The DRAM requests file is :sixbar.req

The requests file will be created, if the graphics is requested in the DRAM input language program. Otherwise, a message "No request file produced by this run" will be displayed on the screen.

"Do you want to delete your DRAM executable files (Y/N) (<cr>=N)"--------

This message displays when the subprogram is linked to DRAM.

The answer should be "NO" if the program needs to be run a second time. With a "NO" answer, DRAM saves the DRAM.EXE file. Otherwise, the answer is "YES".

CHAPTER 7

EXAMPLE PROBLEMS

This chapter illustrates the various examples. The first two examples are documentated in detail and the rest of examples are commented where new statements are introduced. The input data values such as the lengths and the angles must be accurate to make the system of closed loop type. That is why, in the following examples, that considerable number of digits are needed. The accuracy can also be improved by considering that additional number of digits for the masses, the mass moment of inertias etc. Smooth curves of the DRAM graphs can be obtained by increasing the number of steps in the OUTPUT statement of input data coding of DRAM.

7.1 EXAMPLE:

A slender rod, having a mass of 1.3685894 lbf sec sq./ft is released from its equilibrium position. Initially, the rod makes an angle of 45 degrees with the horizontal x-axis. Determine the angular displacement and angular velocity of the oscillation. The length and mass of moment of inertia of the slender rod are 4.9166667 ft. and 11.01075 lbf ft sec sq. respectively. Consider the gravitational constant = 1 .

SLENDER ROD

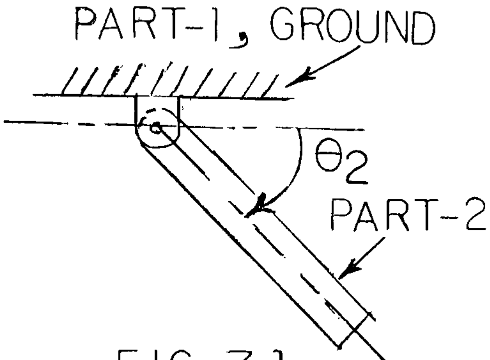


FIG. 7.1

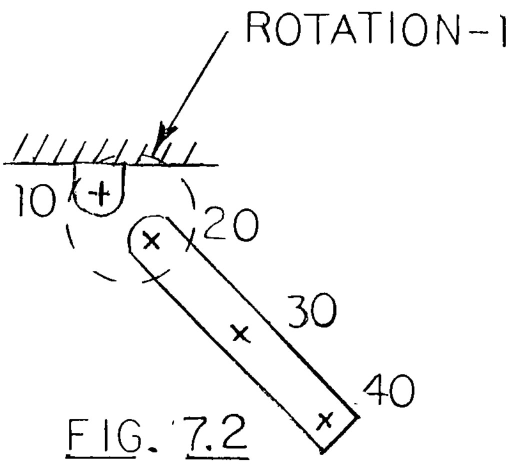


FIG. 7.2

MARKERS

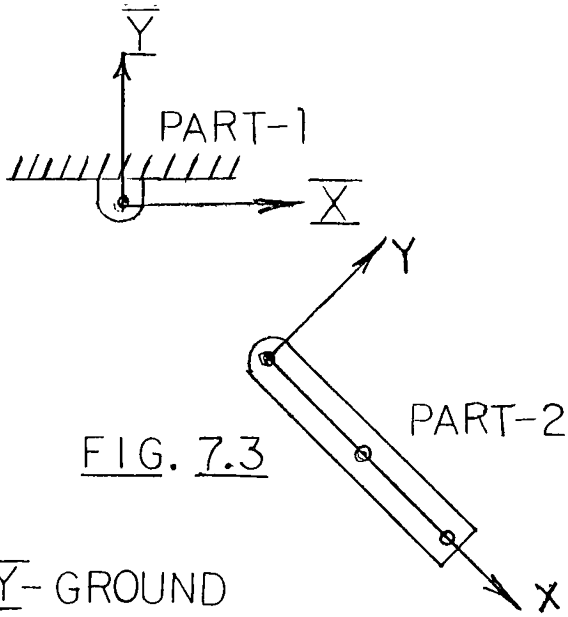


FIG. 7.3

$\overline{X}\,\overline{Y}$ - GROUND REFERENCE AXIS

XY - LOCAL PART REFERENCE AXIS

SLENDER ROD

THE FIRST LINE OF THE PROGRAM IS THE PROBLEM TITLE OR OTHERWISE BLANK.

LIST

THE LIST STATEMENT PRODUCES THE LISTING OF PROGRAM IN THE OUTPUT FILE AND CAN BE OMITTED IF THE LISTING OF PROGRAM IS NOT NEEDED.

DESCRIPTION OF EACH PART

PART/1,GROUND

PART 1 IS FIXED TO THE GROUND.

MARKER/10,POINT,PART=1,X=0,Y=0

PART 1 HAS A ATTACHED MARKER 10 WHICH IS A POINT. THE GROUND REFERENCE COORDINATES OF MARKER 10 ARE (X,Y)==>(0,0).

PART/2,MASS=1.3685894,CM=30,INERTIA=11.010755,ANGLE=-45

THE CENTER OF MASS OF THE SLENDER ROD IS AT MARKER 30. THE INITIAL ANGULAR DISPLACEMENT ANGLE IS NEGATIVE BECAUSE IT IS MEASURED IN THE CLOCKWISE DIRECTION FROM THE GROUND REFERENCE AXIS.

MARKER/20,GMARKER,PART=2,X=0,Y=0,ANGLE=0

THE GMARKER IS A POINT AND A UNIT VECTOR. A UNIT VECTOR LIES ALONG THE DESCRIBED AXIS SYSTEM OF THE PART. THE ANGLE IS CONSIDERED ZERO BECAUSE IT IS MEASURED WITH RESPECT TO THE LOCAL PART REFERENCE AXIS AND NOT WITH RESPECT TO THE GROUND REFERENCE AXIS. THE COORDINATES OF GMARKER 20 ARE (X,Y)==>(0,0).

MARKER/30,POINT,PART=2,X=2.4583333,Y=0

MARKER 30 IS LOCATED AT A DISTANCE 2.4583333 FEET FROM THE ORIGIN OF THE LOCAL PART REFERENCE AXIS.

MARKER/40,POINT,PART=2,X=4.9166667,Y=0

MARKER 40 IS LOCATED AT A DISTANCE 4.9166667 FEET FROM THE ORIGIN OF THE LOCAL PART REFERENCE AXIS.

NOTE: IN THE PART DESCRIPTION, THERE MUST BE AT LEAST ONE "GMARKER" STATEMENT IN THE DEFINED MARKERS.

ROTATION/1,I=10,J=20

#1 IS THE NUMBER OF THE ROTATIONAL CONTACT: THE IDENTIFICATION NUMBERS I AND J DESCRIBE THE ROTATIONAL CONTACT BETWEEN TWO MARKERS.

SYSTEM/GC=1,JGRAV=-32.2,ERR=1.E-4,IC

THE SYSTEM INCLUDES ALL PARTS PLUS ALL ROTATIONS AND TRANSLATIONS.

GC==> GRAVITATIONAL CONSTANT.

JGRAV==> GRAVITATIONAL ACCELERATION VECTOR IN THE Y DIRECTION.

ERR==> MAXIMUM ALLOWED RELATIVE ERROR PER INTEGRATION STEP. DEFAULTS TO 1.E-4. HOWEVER THE USER MAY SELECT HIGHER OR LOWER NUMBER FOR RELATIVE ERROR PER INTEGRATION STEP.

IC==> DEFAULT VALUE OF IC IS 1. HENCE THE ITERATIONS ARE PERFORMED IN ORDER TO DETERMINE THE CONSISTENT INITIAL CONDITIONS WITHIN THE NUMBER OF DIGITS ACCURACY SPECIFIED BY ACC. WHERE ACC ==> NUMBER OF SIGNIFICANT DIGITS ACCURACY. SINCE ACC IS NOT SPECIFIED IN THE SYSTEM STATEMENT IT DEFAULTS TO 15.

DESCRIPTION OF OUTPUT REQUESTS

OUTPUT/END=2.5,STEPS=50

```
      END==> COMPLETE CYCLE TIME= 360/ANGULAR VELOCITY IN DEGREES/
      SEC. HOWEVER IN THIS PROBLEM 2.5 SECONDS ARE USED BY INSPECTION.
      DURING THIS TIME THE SLENDER ROD COMPLETE ITS CYCLE.
      STEP==> NO. OF TIME INTERVAL STEPS.

REQUEST/1,DISPLACEMENT,I=40,J=10
      THE OUTPUT GIVES THE DISPLACEMENT OF MARKER 40 WITH RESPECT
      TO MARKER 10.
REQUEST/2,VELOCITY,I=40,J=10
      THE OUTPUT GIVES THE VELOCITY OF MARKER 40 WITH RESPECT TO
      MARKER 10.

REQUEST/3,MINMAX,I=40,J=10,ALL
      MINMAX PRODUCES A TABLE OF THE MINIMUM AND MAXIMUM VALUES
      OF ALL THE REQUESTS AND THE TIME AT WHICH THE MIN-MAX VALUES
      OCCURED. IF "ALL" IS ENTERED VALUES ARE DETERMINED AT EACH
      SUCCESSFUL INTEGRATION STEP. OTHERWISE, VALUES ARE DETERMINED
      AT EACH OUTPUT STEP.

      NOTE: THE VALUE OF "ERR" MAY BE CHOSEN HIGHER OR LOWER
      DEPENDING ON HOW MUCH RELATIVE ERROR IS ACCEPTABLE IN THE
      EXAMPLE.
 END
```

OUTPUTS

Output results can be read as follows:

The System has 1 degree of freedom. Hence, it will be simulated in the dynamic mode.

Request 1 : Since there is no linear displacement the values of angles are considered as the angular displacement by DRAM. These values are plotted by substracting the angle theta-2 from 360 degrees. It is noticed from the normalized plot that the normalized values are plotted with number 3. Number 3 describes that the plotted values are the values of the third column of output results. The origin of the normalized plot is at the top left corner. Displacement values are plotted along the horizontal X axis of the page whereas time values are plotted along the vertical Y axis of the page. It is also important to notice that all values in the column two are the constant length values of the slender rod. DRAM plots the value of the length when there is no linear displacement in the described mechanism. As a result of this MAX and MIN values in the DRAM MIN-MAX TABLE will be the same in the magnitude which can be seen clearly in the DRAM MIN-MAX TABLE of this particular example.

Request 2 : In this request the values of angles are considered as the angles made by the velocities at different time intervals. The angle is measured in the counterclockwise direction from the global x axis and is positive according to DRAM sign convenction. In the normalized plot, 2 ==> describes angular velocity although the output shows the linear velocity (DRAM software has been set up this way), and 3 ==> describes angles which are made by the velocities. The normalized plot shows jumps in the plot (on page79). These jumps are caused by the oscillation of the slender rod.

Request 3 : Provides all maximum and minimum values of request 1 and request 2.

SLENDER ROD

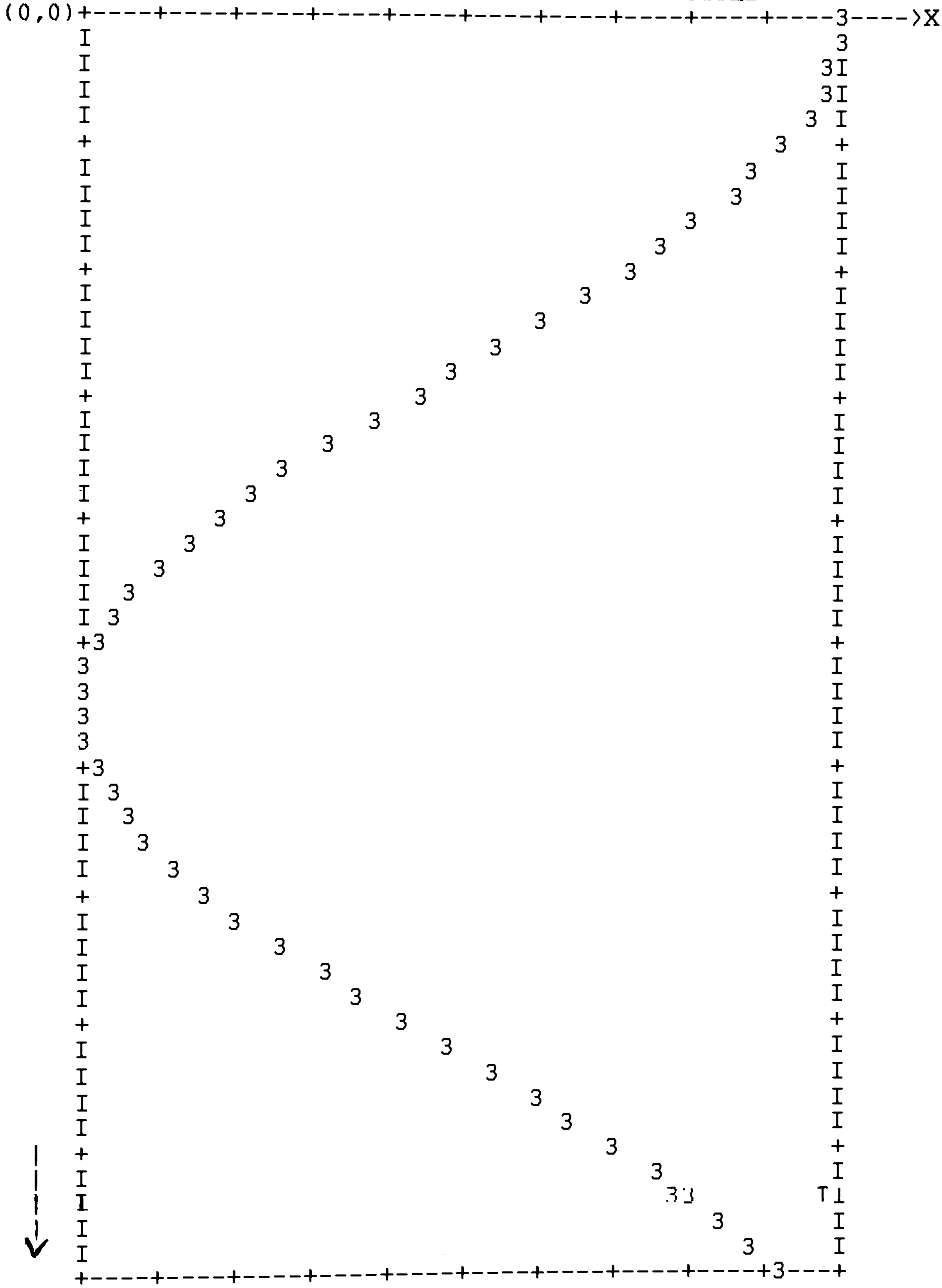
REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR DISPLACEMENT OF MARKER 40 RELATIVE TO MARKER 10	ANGLE (DEGREES)
0.0000E+00	4.91667E+00	3.15000E+02
5.0000E-02	4.91667E+00	3.14715E+02
1.0000E-01	4.91667E+00	3.13866E+02
1.5000E-01	4.91667E+00	3.12460E+02
2.0000E-01	4.91667E+00	3.10510E+02
2.5000E-01	4.91667E+00	3.08039E+02
3.0000E-01	4.91667E+00	3.05074E+02
3.5000E-01	4.91667E+00	3.01648E+02
4.0000E-01	4.91667E+00	2.97800E+02
4.5000E-01	4.91667E+00	2.93578E+02
5.0000E-01	4.91667E+00	2.89035E+02
5.5000E-01	4.91667E+00	2.84231E+02
6.0000E-01	4.91667E+00	2.79229E+02
6.5000E-01	4.91667E+00	2.74100E+02
7.0000E-01	4.91667E+00	2.68911E+02
7.5000E-01	4.91667E+00	2.63737E+02
8.0000E-01	4.91667E+00	2.58651E+02
8.5000E-01	4.91667E+00	2.53722E+02
9.0000E-01	4.91667E+00	2.49019E+02
9.5000E-01	4.91667E+00	2.44604E+02
1.0000E+00	4.91667E+00	2.40534E+02
1.0500E+00	4.91667E+00	2.36856E+02
1.1000E+00	4.91667E+00	2.33619E+02
1.1500E+00	4.91667E+00	2.30857E+02
1.2000E+00	4.91667E+00	2.28602E+02
1.2500E+00	4.91667E+00	2.26879E+02
1.3000E+00	4.91667E+00	2.25704E+02
1.3500E+00	4.91667E+00	2.25091E+02
1.4000E+00	4.91667E+00	2.25045E+02
1.4500E+00	4.91667E+00	2.25567E+02
1.5000E+00	4.91667E+00	2.26651E+02
1.5500E+00	4.91667E+00	2.28287E+02
1.6000E+00	4.91667E+00	2.30457E+02
1.6500E+00	4.91667E+00	2.33139E+02
1.7000E+00	4.91667E+00	2.36302E+02
1.7500E+00	4.91667E+00	2.39911E+02
1.8000E+00	4.91667E+00	2.43923E+02
1.8500E+00	4.91667E+00	2.48287E+02
1.9000E+00	4.91667E+00	2.52948E+02
1.9500E+00	4.91667E+00	2.57844E+02
2.0000E+00	4.91667E+00	2.62909E+02
2.0500E+00	4.91667E+00	2.68072E+02
2.1000E+00	4.91667E+00	2.73264E+02
2.1500E+00	4.91667E+00	2.78411E+02
2.2000E+00	4.91667E+00	2.83441E+02
2.2500E+00	4.91667E+00	2.88284E+02
2.3000E+00	4.91667E+00	2.92873E+02
2.3500E+00	4.91667E+00	2.97151E+02
2.4000E+00	4.91667E+00	3.01064E+02
2.4500E+00	4.91667E+00	3.04562E+02
2.5000E+00	4.91667E+00	3.07605E+02

Note:
THE LINEAR DISPLACEMENT VALUES DO NOT CHANGE BECAUSE THE LENGTH OF THE ROD IS FIXED, AND MARKER 40 REMAINS FIXED WITH RESPECT TO MARKER 10. THE ANGULAR DISPLACEMENT IS GIVEN IN THE ANGLE COLUMN.

NORMALIZED PLOT OF THE OUTPUT

THE PLOTTED CHARACTER INDICATES THE PARTICULAR
COLUMN OF TABULATED DATA BEING PLOTTED



SLENDER ROD

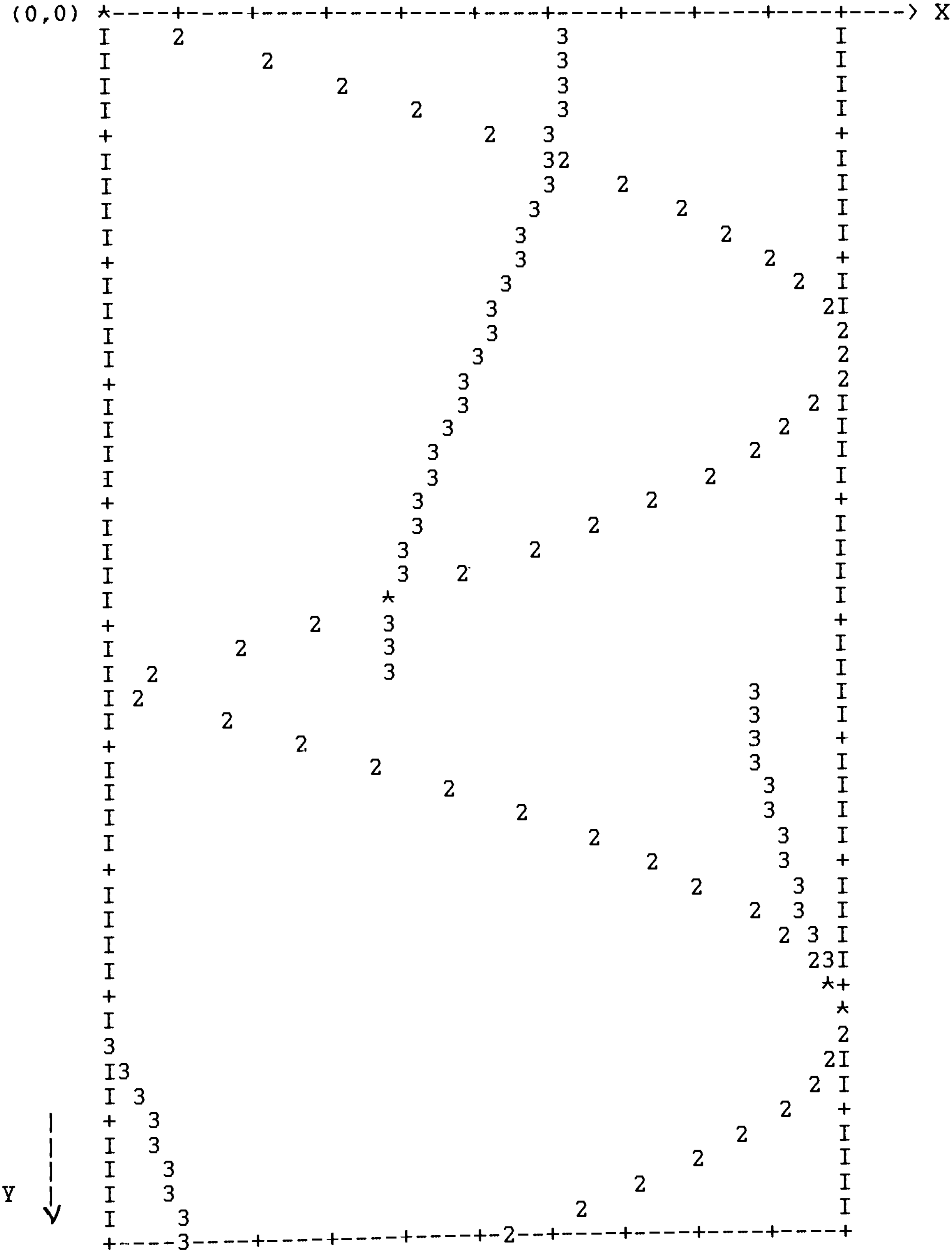
REQUEST NUMBER 2

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 40 RELATIVE TO MARKER 10		ANGLE (DEGREES)	
0.0000E+00	0.00000E+00		0.00000E+00	
5.0000E-02	9.74173E-01		2.24715E+02	
1.0000E-01	1.93864E+00		2.23866E+02	
1.5000E-01	2.88345E+00		2.22460E+02	
2.0000E-01	3.79844E+00		2.20510E+02	
2.5000E-01	4.67281E+00		2.18039E+02	
3.0000E-01	5.49541E+00		2.15074E+02	
3.5000E-01	6.25487E+00		2.11648E+02	
4.0000E-01	6.93957E+00		2.07800E+02	
4.5000E-01	7.53815E+00		2.03578E+02	
5.0000E-01	8.03987E+00		1.99035E+02	
5.5000E-01	8.43507E+00		1.94231E+02	
6.0000E-01	8.71574E+00		1.89229E+02	
6.5000E-01	8.87689E+00		1.84100E+02	
7.0000E-01	8.91330E+00	MAX.	1.78911E+02	
7.5000E-01	8.82488E+00		1.73737E+02	
8.0000E-01	8.61356E+00		1.68651E+02	
8.5000E-01	8.28390E+00		1.63722E+02	
9.0000E-01	7.84278E+00		1.59019E+02	
9.5000E-01	7.29828E+00		1.54604E+02	
1.0000E+00	6.66230E+00		1.50534E+02	
1.0500E+00	5.94488E+00		1.46856E+02	
1.1000E+00	5.15753E+00		1.43619E+02	
1.1500E+00	4.31190E+00		1.40857E+02	
1.2000E+00	3.41920E+00		1.38602E+02	
1.2500E+00	2.49043E+00		1.36879E+02	
1.3000E+00	1.53606E+00		1.35705E+02	
1.3500E+00	5.66202E-01		1.35091E+02	
1.4000E+00	4.09316E-01		3.15045E+02	
1.4500E+00	1.38077E+00		3.15567E+02	
1.5000E+00	2.33837E+00		3.16651E+02	
1.5500E+00	3.27206E+00		3.18287E+02	
1.6000E+00	4.17141E+00		3.20457E+02	
1.6500E+00	5.02555E+00		3.23139E+02	
1.7000E+00	5.82320E+00		3.26302E+02	
1.7500E+00	6.55283E+00		3.29911E+02	
1.8000E+00	7.20289E+00		3.33923E+02	
1.8500E+00	7.76221E+00		3.38287E+02	
1.9000E+00	8.22043E+00		3.42948E+02	
1.9500E+00	8.56854E+00		3.47844E+02	
2.0000E+00	8.79933E+00		3.52909E+02	
2.0500E+00	8.90887E+00		3.58072E+02	MAX.
2.1000E+00	8.89288E+00		3.26431E+00	
2.1500E+00	8.75253E+00		8.41104E+00	
2.2000E+00	8.49086E+00		1.34405E+01	
2.2500E+00	8.11346E+00		1.82836E+01	
2.3000E+00	7.62723E+00		2.28733E+01	
2.3500E+00	7.04356E+00		2.71510E+01	
2.4000E+00	6.37194E+00		3.10641E+01	
2.4500E+00	5.62366E+00		3.45622E+01	
2.5000E+00	4.81041E+00		3.76050E+01	

NOTE: THE VALUES OF VELOCITY ARE NOT THE LINEAR VELOCITY VALUES, BUT ARE THE ANGULAR VELOCITY VALUES. DRAM HAS BEEN SET UP IN THIS MANNER.

NORMALIZED PLOT OF THE OUTPUT

THE PLOTTED CHARACTER INDICATES THE PARTICULAR
COLUMN OF TABULATED DATA BEING PLOTTED



```
*********************************************************************
*                                                                   *
*   SLENDER ROD                                                     *
*                                                                   *
*   REQUEST NO.    3      DRAM MIN-MAX TABLE                        *
*                                                                   *
*   MINMAX SEARCH AFTER EVERY INTEGRATION                           *
*                                                                   *
*********************************************************************


   REQUEST NUMBER      1

                       **** DISPLACEMENT ****
         MEASURED FROM MARKER    40 RELATIVE TO MARKER    10
   TIME                       POLAR COORDINATES
                    MAGNITUDE          ANGLE (DEG)

   2.5000E+00  MAX  4.916667            307.6050
   2.4000E+00  MIN  4.916667            301.0641

   3.2250E-03       4.916667      MAX  315.0000
   1.4000E+00       4.916667      MIN  225.0452


   REQUEST NUMBER      2

                         **** VELOCITY ****
         MEASURED FROM MARKER    40 RELATIVE TO MARKER    10
   TIME                       POLAR COORDINATES
                    MAGNITUDE          ANGLE (DEG)

   7.0000E-01  MAX  8.913299            178.9112
   3.2250E-03  MIN 0.0000000E+00       0.0000000E+00

   2.0500E+00       8.908869      MAX  358.0720
   3.2250E-03      0.0000000E+00  MIN 0.0000000E+00
```

7.2 EXAMPLE:

In a slider crank mechanism, the crank is rotating at a velocity of 3000 rpm (1800 deg/sec). The direction of rotation of the crank is counterclockwise. An external force of 11.024845 lbf is applied to the slider in the negative x-direction. The position of the slider is 0.0252292 ft. above the center of rotation of the crank. Calculate the velocity and acceleration of the slider. Also calculate the force exerted by the slider on the connecting rod, and the angular velocity and angular acceleration of the connecting rod. Consider the length of the crank =0.16666667 ft., the length of the connecting rod =0.66666667 ft., the mass of the crank =0.00776398 lbf sec sq./ft, the mass of the connecting rod =0.0310559 lbf sec sq./ft , the mass of the slider =0.04658385 lbf sec sq./ft ,the mass moment of inertia of the crank =0.00001797 lbf ft sec sq. , the mass moment of inertia of the connecting rod =0.00115021 lbf ft sec sq. , and the mass moment of inertia of the slider=0.00000674 lbf ft sec sq. The crank is rotating at a constant velocity, and its initial position is 30 degrees (ccw) as shown in the figure 7.4. Consider theta 3 =5 degrees (cw) and initial translational position of the slider is 0.125 ft (horizontal direction). The length of the slider is 0.0833333 inches. Angles measured in the clockwise direction are negative.

SLIDER CRANK

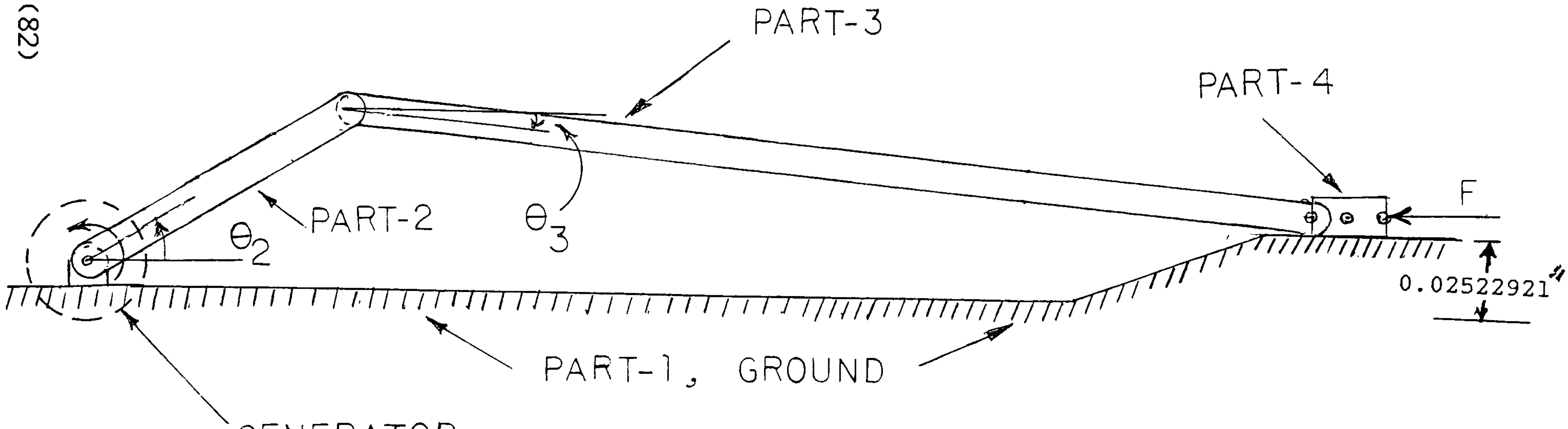


FIG. 7.4 - POSITION

SLIDER CRANK

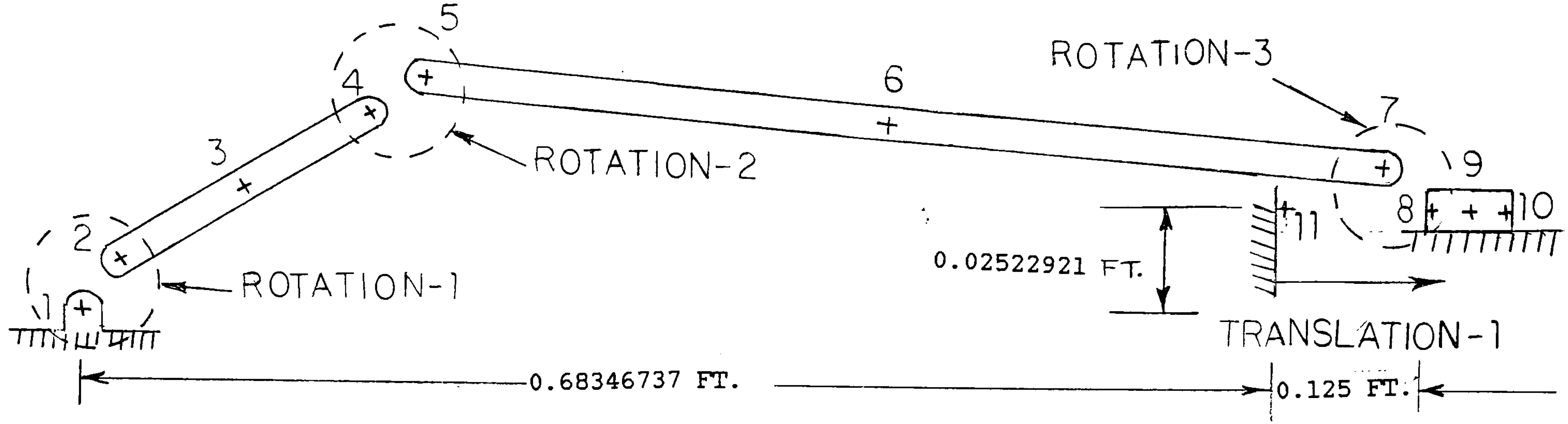


FIG. 7.5 - MARKERS

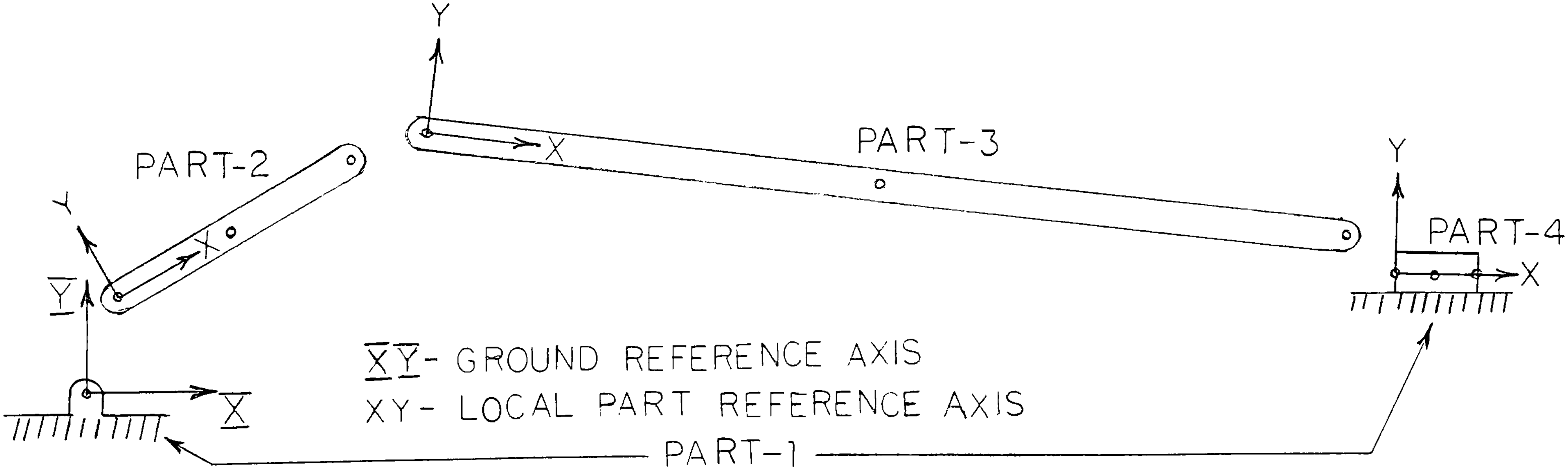


FIG. 7.6 - AXES

SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE

THE FIRST LINE OF THE PROGRAM MUST BE THE NAME OF THE MECHANISM OR OTHERWISE BLANK.

LIST

THE LIST STATEMENT PRODUCES THE LISTING OF PROGRAM IN THE OUTPUT FILE AND CAN BE OMITTED IF THE LISTING OF PROGRAM IS NOT NEEDED.

DESCRIPTION OF EACH PART

PART/1,GROUND

PART 1 IS FIXED TO THE GROUND.

MARKER/1,POINT,PART=1,X=0,Y=0

PART 1 HAS AN ATTACHED MARKER 1 WHICH IS A POINT. THE GROUND REFERENCE COORDINATES OF MARKER 1 ARE (X,Y)==>(0,0)

MARKER/11,GMARKER,PART=1,X=0.68346737,Y=0.02522921,ANGLE=0

MARKER 11 IS A POINT AND IS LOCATED AT DISTANCE X=0.68346737, Y=0.02522921 FROM THE COORDINATES OF MARKER 1. SINCE THE SLIDER HAS A TRANSLATIONAL MOTION MARKER 11 MUST BE A GMARKER.

PART/2,MASS=0.00776398,CM=3,INERTIA=0.00001797,ANGLE=30
,DEGDANGLE=18000

THE CENTER OF MASS OF PART 2 IS AT A MARKER 3. THE VALUES OF MASS, AND MASS MOMENT OF INERTIA ARE ASSIGNED FROM THE GIVEN PROBLEM. PART 2 MAKES AN ANGLE OF 30 DEGREES WITH RESPECT TO THE GROUND REFERENCE AXIS SYSTEM. DEGDANGLE==> INITIAL ANGULAR VELOCITY OF PART 2 IN DEGREES/SEC [(RAD/SEC) X 180/3.142]. THE STATEMENT DEGDANGLE IS CONTINUED ON THE NEXT LINE BY PUTTING A COMMA (,) IN THE FIRST COLUMN OF NEXT THE LINE. THE OTHER OPTION WOULD BE TO TYPE 'PART/2, DEGDANGLE=18000' ON THE NEXT LINE.

MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0

THE GMARKER IS A POINT AND A UNIT VECTOR. THE COORDINATES OF GMARKER 2 ARE (X,Y)==>(0,0) [LOCAL PART REFERENCE COORDINATES].

MARKER/3,POINT,PART=2,X=0.08333333,Y=0

MARKER 3 IS A POINT ONLY. MARKER 3 IS LOCATED AT A DISTANCE X=0.08333333,Y=0 FROM MARKER 2.

MARKER/4,POINT,PART=2,X=0.16666667,Y=0

MARKER 4 IS A POINT ONLY. MARKER 4 IS LOCATED AT A DISTANCE X=0.16666667,Y=0 FROM MARKER 2.

PART/3,MASS=0.0310559,CM=6,INERTIA=0.00115021,ANGLE=-5

THE CENTER OF MASS OF PART 3 IS AT MARKER 6. THE VALUES OF THE MASS, AND MASS MOMENT OF INERTIA ARE ASSIGNED FROM THE GIVEN PROBLEM. PART 3 MAKES AN ANGLE -5 DEGREES (MEASURED IN CLOCKWISE DIRECTION) WITH RESPECT TO THE GROUND REFERENCE COORDINATE SYSTEM.

MARKER/5,GMARKER,PART=3,X=0,Y=0,ANGLE=0

THE GMARKER IS A POINT AND A UNIT VECTOR. THE COORDINATES OF GMARKER 5 ARE (X,Y)==>(0,0) [LOCAL PART REFERENCE COORDINATES]. THE ANGLE MUST BE ZERO SINCE MARKER 5 IS AT THE ORIGIN.

MARKER/6,POINT,PART=3,X=0.33333333,Y=0

MARKER 6 IS A POINT ONLY. MARKER 6 IS LOCATED AT A DISTANCE X=0.33333333,Y=0 FROM MARKER 5.

MARKER/7,POINT,PART=3,X=0.66666667,Y=0

MARKER 7 IS A POINT ONLY. MARKER 7 IS LOCATED AT A DISTANCE X=0.66666667,Y=0 FROM MARKER 5.

PART/4,MASS=0.04658385,CM=9,INERTIA=0.00000674,ANGLE=0

THE CENTER OF MASS OF PART 4 IS AT MARKER 9. THE VALUES OF THE

MASS, AND MASS MOMENT OF INERTIA ARE ASSIGNED FROM THE GIVEN PROBLEM. PART 4 MAKES AN ANGLE OF 0 DEGREES.

```
MARKER/8,GMARKER,PART=4,X=0,Y=0,ANGLE=0
```

THE GMARKER IS A POINT. THE COORDINATES OF GMARKER 2 ARE (X,Y)==>(0,0) [LOCAL PART REFERENCE COORDINATES]. SINCE THE SLIDER HAS A TRANSLATIONAL MOTION MARKER 8 MUST BE A GMARKER.

```
MARKER/9,POINT,PART=4,X=0.04166667,Y=0
```

MARKER 9 IS A POINT ONLY. MARKER 9 IS LOCATED AT A DISTANCE X=0.04166667,Y=0 FROM MARKER 8.

```
MARKER/10,POINT,PART=4,X=0.08333333,Y=0
```

MARKER 10 IS A POINT ONLY. MARKER 10 IS LOCATED AT A DISTANCE X=0.08333333,Y=0 FROM MARKER 8.

```
ROTATION/1,I=1,J=2
```

#1 IS THE NUMBER OF THE ROTATIONAL CONTACT. IDENTIFICATION NUMBERS I AND J DESCRIBE THE ROTATIONAL CONTACT BETWEEN THE TWO MARKERS.

```
ROTATION/2,I=4,J=5
```

#2 IS THE NUMBER OF THE ROTATIONAL CONTACT. IDENTIFICATION NUMBERS I AND J DESCRIBE THE ROTATIONAL CONTACT BETWEEN THE TWO MARKERS.

```
ROTATION/3,I=7,J=8
```

#3 IS THE NUMBER OF THE ROTATIONAL CONTACT. IDENTIFICATION NUMBERS I AND J DESCRIBE THE ROTATIONAL CONTACT BETWEEN THE TWO MARKERS.

```
TRANSLATION/1,I=8,J=11,TRANSLATION=0.125
```

#1 IS THE NUMBER OF THE TRANSLATION CONTACT. IDENTIFICATION NUMBERS I AND J DESCRIBE THE TRANSLATIONAL CONTACT BETWEEN THE TWO MARKERS. THE INITIAL TRANSLATIONAL DISPLACEMENT IS 0.125 FT. THAT IS, THE SLIDER IS AT 0.125 FT. AWAY FROM MARKER 11 INITIALLY.

```
FIELD/1,TRANSLATIONAL,CONSTANT,I=10,ANGLE=180,PAR=11.024845
```

A FIELD IS AN APPLIED FORCE EXERTED BETWEEN A PAIR OF MARKERS.
#1 IS THE FIELD IDENTIFICATION NUMBER.
CONSTANT==> CONSTANT APPLIED FORCE AT AN ANGLE 180 DEGREE.
PAR==> MAGNITUDE OF THE FORCE (11.024845 LBS) IN LBS.

```
GENERATOR/1,ROTATIONAL,ON=2,CONSTANT VELOCITY,DEGPAR=18000,PAR=30.0D
```

A GENERATOR INPUT A ROTATIONAL MOTION TO A MECHANICAL SYSTEM. #1 IS THE GENERATOR IDENTIFICATION NUMBER. DEGPAR==> ANGULAR VELOCITY IN DEGREES/SEC. PAR==> INITIAL POSITION OF PART 2 WHICH IS 30 DEGREES. THIS ROTATIONAL GENERATOR ACTS ON PART 2 (ON=2).

```
SYSTEM/GC=1,JGRAV=-32.2,ERR=1.E-4,IC
```

THE SYSTEM INCLUDES ALL PARTS PLUS ALL ROTATIONS AND TRANSLATIONS.
GC==> GRAVITATIONAL CONSTANT.
JGRAV==> GRAVITATIONAL ACCELERATION VECTOR IN THE Y DIRECTION. THE POSITIVE "Y" DIRECTION IS UPWARD WHILE THE NEGATIVE "Y" DIRECTION IS DOWNWARD ALWAYS.
ERR==> MAXIMUM ALLOWED RELATIVE ERROR PER INTEGRATION STEP. DEFAULTS TO 1.E-4.

DESCRIPTION OF OUTPUT REQUESTS

```
OUTPUT/END=0.02,STEPS=50,NOPLOT,RANGLE
```

END==> COMPLETE CYCLE TIME AND IS CALCULATED BY USING THE FORMULA:
CYCLE TIME= 360/ANGULAR VELOCITY IN DEGREES/SEC.
STEP==> NO. OF TIME INTERVAL STEPS.
NOPLOT==> NO STRIP-CHART (NORMALIZED PLOT) IS PRINTED.
RANGLE==> ALL CALCULATED ANGLES ARE IN RADIANS. DEFAULTS TO

DEGREES.

REQUEST/1,VELOCITY,I=9,J=1
THE OUTPUT GIVES THE LINEAR VELOCITY OF MARKER 9 WITH RESPECT TO MARKER 1.
REQUEST/2,VELOCITY,I=6,J=1
THE OUTPUT GIVES THE ANGULAR VELOCITY OF MARKER 6 WITH RESPECT TO MARKER 1.
REQUEST/3,ACCELERATION,I=5,J=1
THE OUTPUT GIVES THE ANGULAR ACCELERATION OF MARKER 5 WITH RESPECT TO MARKER 1.
REQUEST/4,ACCELERATION,I=9,J=1
THE OUTPUT GIVES THE LINEAR ACCELERATION OF MARKER 9 WITH RESPECT TO MARKER 1.

REQUEST/5,FORCE,I=8,J=7
THE OUTPUT GIVES THE FORCE EXERTED BY MARKER 7 ON MARKER 8.

END

OUTPUTS

Output results can be read as follows:

Since the system has zero degrees of freedom the system will be simulated in kinematic mode. This also is a closed loop system. The crank, the connecting rod and the slider form a closed loop in the slider crank mechanism. In this type of example, the angular velocity of the crank needs to be supplied. DRAM will calculate angular velocities of the other components of the mechanism by considering the geometry. DRAM also corrects the input data values and gives the amount of error between the input data values and the corrected values (by DRAM). The input data values are the lengths and angles. These input values must be accurate in order to make the mechanical system of close loop type. Otherwise DRAM will give an error message. That is why the maximum number of digits for the lengths and angles are employed after the decimal point in the examples. In the output, corrected initial values are considered as Corrected Initial Conditions. PART/1 of first page of the output explains the angular displacement in degrees and the angular velocity in rad/sec of part 1 respectively. Similarly, the angular displacement and angular velocity of part 2 and part 3 are explained. TRAN/1 explains the translational displacement and velocity of part 4 respectively. (DRAM does not print the units some how.) No normalized plot is plotted since the "NOPLOT" request is made in the output statement of the program.

Request 1 and 2 : The angle made by the velocity vector at every time interval is given in the ANGLE column. The angles are measured form the positive X axis. The angle in clockwise direction is negative. The angle values are given in radians because of the RANGLE request (made in the output statement).

Request 3 and 4 : The angle made by the acceleration vector at every time interval is given in the ANGLE column. The angle values are given in radians because of the RANGLE request (made in the output statement). Request 5 : The angle made by the force vector at every time interval is given in the ANGLE column. The angle values are given in radians because of the RANGLE request (made in the output statement).

```
SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE


-- DEFAULT VALUE (TSM1) -- SYSTEM/TS= 4.0000E-04

SYSTEM HAS    0 DEGREE(S) OF FREEDOM
SYSTEM WILL BE SIMULATED IN KINEMATIC MODE



*---- INPUT DATA LOOP CLOSURE CHECK  ----*
I---------------------------------------I
I ROTATION I DISPLACEMENT I   VELOCITY   I
I          I    ERROR     I    ERROR     I
I----------I--------------I--------------I
I        3 I  2.96219D-07 I  5.23599D+01 I
I----------I--------------I--------------I


LOOP CLOSURE DISPLACEMENT SOLUTION

CONVERGENCE WITHIN   4.08581D-17 IN  3 ITERATIONS

LOOP CLOSURE VELOCITY SOLUTION


CORRECTED INITIAL CONDITIONS

                     DISPLACEMENT                            VELOCITY
PART/     1     0.000000000000000D+00 DEG    0.000000000000000D+00 RAD/SEC
PART/     2     3.000000000000000D+01 DEG    3.141592653589793D+02 RAD/SEC
PART/     3    -5.000025554707580D+00 DEG   -6.827729555624298D+01 RAD/SEC
TRAN/     1     1.249999763174624D-01       -3.014713181917561D+01

KFLAG= 0 ORDER= 0 IFCT=    51 H= 0.40000D-03 ITER=     3


IN THE OUTPUT PHASE  1548 WORDS OF MEMORY WERE REQUIRED
```

SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE

REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 9 RELATIVE TO MARKER 1	ANGLE (RADIANS)
0.0000E+00	3.01471E+01	3.14159E+00
4.0000E-04	3.64129E+01	3.14159E+00
8.0000E-04	4.18110E+01	3.14159E+00
1.2000E-03	4.62408E+01	3.14159E+00
1.6000E-03	4.96362E+01	3.14159E+00
2.0000E-03	5.19668E+01	3.14159E+00
2.4000E-03	5.32382E+01	3.14159E+00
2.8000E-03	5.34896E+01	3.14159E+00
3.2000E-03	5.27894E+01	3.14159E+00
3.6000E-03	5.12292E+01	3.14159E+00
4.0000E-03	4.89159E+01	3.14159E+00
4.4000E-03	4.59645E+01	3.14159E+00
4.8000E-03	4.24901E+01	3.14159E+00
5.2000E-03	3.86014E+01	3.14159E+00
5.6000E-03	3.43957E+01	3.14159E+00
6.0000E-03	2.99563E+01	3.14159E+00
6.4000E-03	2.53501E+01	3.14159E+00
6.8000E-03	2.06287E+01	3.14159E+00
7.2000E-03	1.58288E+01	3.14159E+00
7.6000E-03	1.09753E+01	3.14159E+00
8.0000E-03	6.08300E+00	3.14159E+00
8.4000E-03	1.16069E+00	3.14159E+00
8.8000E-03	3.78625E+00	0.00000E+00
9.2000E-03	8.75213E+00	0.00000E+00
9.6000E-03	1.37276E+01	0.00000E+00
1.0000E-02	1.86959E+01	0.00000E+00
1.0400E-02	2.36299E+01	0.00000E+00
1.0800E-02	2.84885E+01	0.00000E+00
1.1200E-02	3.32146E+01	0.00000E+00
1.1600E-02	3.77330E+01	0.00000E+00
1.2000E-02	4.19510E+01	0.00000E+00
1.2400E-02	4.57594E+01	0.00000E+00
1.2800E-02	4.90369E+01	0.00000E+00
1.3200E-02	5.16555E+01	0.00000E+00
1.3600E-02	5.34888E+01	0.00000E+00
1.4000E-02	5.44202E+01	0.00000E+00
1.4400E-02	5.43521E+01	0.00000E+00
1.4800E-02	5.32139E+01	0.00000E+00
1.5200E-02	5.09680E+01	0.00000E+00
1.5600E-02	4.76141E+01	0.00000E+00
1.6000E-02	4.31907E+01	0.00000E+00
1.6400E-02	3.77737E+01	0.00000E+00
1.6800E-02	3.14743E+01	0.00000E+00
1.7200E-02	2.44335E+01	0.00000E+00
1.7600E-02	1.68177E+01	0.00000E+00
1.8000E-02	8.81136E+00	0.00000E+00
1.8400E-02	6.11353E-01	0.00000E+00
1.8800E-02	7.58036E+00	3.14159E+00
1.9200E-02	1.55632E+01	3.14159E+00
1.9600E-02	2.31448E+01	3.14159E+00
2.0000E-02	3.01471E+01	3.14159E+00

SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE

REQUEST NUMBER 2

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 6 RELATIVE TO MARKER 1	ANGLE (RADIANS)
0.0000E+00	3.61556E+01	2.46379E+00
4.0000E-04	3.99152E+01	2.59189E+00
8.0000E-04	4.34544E+01	2.69660E+00
1.2000E-03	4.65690E+01	2.78488E+00
1.6000E-03	4.91208E+01	2.86187E+00
2.0000E-03	5.10235E+01	2.93135E+00
2.4000E-03	5.22327E+01	2.99621E+00
2.8000E-03	5.27392E+01	3.05871E+00
3.2000E-03	5.25631E+01	3.12073E+00
3.6000E-03	5.17491E+01	3.18394E+00
4.0000E-03	5.03608E+01	3.24989E+00
4.4000E-03	4.84767E+01	3.32014E+00
4.8000E-03	4.61857E+01	3.39638E+00
5.2000E-03	4.35849E+01	3.48044E+00
5.6000E-03	4.07776E+01	3.57449E+00
6.0000E-03	3.78748E+01	3.68106E+00
6.4000E-03	3.49973E+01	3.80305E+00
6.8000E-03	3.22797E+01	3.94358E+00
7.2000E-03	2.98743E+01	4.10541E+00
7.6000E-03	2.79484E+01	4.28966E+00
8.0000E-03	2.66700E+01	4.49401E+00
8.4000E-03	2.61742E+01	4.71116E+00
8.8000E-03	2.65227E+01	4.92967E+00
9.2000E-03	2.76795E+01	5.13753E+00
9.6000E-03	2.95257E+01	5.32630E+00
1.0000E-02	3.18983E+01	5.49259E+00
1.0400E-02	3.46266E+01	5.63690E+00
1.0800E-02	3.75515E+01	5.76177E+00
1.1200E-02	4.05297E+01	5.87033E+00
1.1600E-02	4.34316E+01	5.96561E+00
1.2000E-02	4.61377E+01	6.05029E+00
1.2400E-02	4.85358E+01	6.12664E+00
1.2800E-02	5.05208E+01	6.19666E+00
1.3200E-02	5.19963E+01	6.26210E+00
1.3600E-02	5.28779E+01	4.14409E-02
1.4000E-02	5.30977E+01	1.02692E-01
1.4400E-02	5.26091E+01	1.64394E-01
1.4800E-02	5.13923E+01	2.28486E-01
1.5200E-02	4.94593E+01	2.97282E-01
1.5600E-02	4.68592E+01	3.73699E-01
1.6000E-02	4.36847E+01	4.61578E-01
1.6400E-02	4.00810E+01	5.66112E-01
1.6800E-02	3.62602E+01	6.94292E-01
1.7200E-02	3.25209E+01	8.54937E-01
1.7600E-02	2.92684E+01	1.05692E+00
1.8000E-02	2.69984E+01	1.30307E+00
1.8400E-02	2.61753E+01	1.58006E+00
1.8800E-02	2.69953E+01	1.85675E+00
1.9200E-02	2.92491E+01	2.10220E+00
1.9600E-02	3.24672E+01	2.30353E+00
2.0000E-02	3.61556E+01	2.46379E+00

SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE

REQUEST NUMBER 3

TIME	MAGNITUDE OF THE LINEAR ACCELERATION OF MARKER 5 RELATIVE TO MARKER 1	ANGLE (RADIANS)	MAGNITUDE OF THE ANGULAR ACCELERATION (RADS) OF MARKER 5 RELATIVE TO MARKER 1
0.0000E+00	1.64493E+04	3.66519E+00	1.19763E+04
4.0000E-04	1.64493E+04	3.79085E+00	1.45625E+04
8.0000E-04	1.64493E+04	3.91652E+00	1.69839E+04
1.2000E-03	1.64493E+04	4.04218E+00	1.91923E+04
1.6000E-03	1.64493E+04	4.16785E+00	2.11345E+04
2.0000E-03	1.64493E+04	4.29351E+00	2.27560E+04
2.4000E-03	1.64493E+04	4.41917E+00	2.40050E+04
2.8000E-03	1.64493E+04	4.54484E+00	2.48377E+04
3.2000E-03	1.64493E+04	4.67050E+00	2.52229E+04
3.6000E-03	1.64493E+04	4.79616E+00	2.51456E+04
4.0000E-03	1.64493E+04	4.92183E+00	2.46087E+04
4.4000E-03	1.64493E+04	5.04749E+00	2.36330E+04
4.8000E-03	1.64493E+04	5.17316E+00	2.22544E+04
5.2000E-03	1.64493E+04	5.29882E+00	2.05201E+04
5.6000E-03	1.64493E+04	5.42448E+00	1.84831E+04
6.0000E-03	1.64493E+04	5.55015E+00	1.61979E+04
6.4000E-03	1.64493E+04	5.67581E+00	1.37165E+04
6.8000E-03	1.64493E+04	5.80147E+00	1.10850E+04
7.2000E-03	1.64493E+04	5.92714E+00	8.34301E+03
7.6000E-03	1.64493E+04	6.05280E+00	5.52280E+03
8.0000E-03	1.64493E+04	6.17847E+00	2.65078E+03
8.4000E-03	1.64493E+04	2.09440E-02	-2.50854E+02
8.8000E-03	1.64493E+04	1.46608E-01	-3.16178E+03
9.2000E-03	1.64493E+04	2.72271E-01	-6.06089E+03
9.6000E-03	1.64493E+04	3.97935E-01	-8.92362E+03
1.0000E-02	1.64493E+04	5.23599E-01	-1.17195E+04
1.0400E-02	1.64493E+04	6.49262E-01	-1.44105E+04
1.0800E-02	1.64493E+04	7.74926E-01	-1.69499E+04
1.1200E-02	1.64493E+04	9.00590E-01	-1.92826E+04
1.1600E-02	1.64493E+04	1.02625E+00	-2.13477E+04
1.2000E-02	1.64493E+04	1.15192E+00	-2.30814E+04
1.2400E-02	1.64493E+04	1.27758E+00	-2.44231E+04
1.2800E-02	1.64493E+04	1.40324E+00	-2.53206E+04
1.3200E-02	1.64493E+04	1.52891E+00	-2.57365E+04
1.3600E-02	1.64493E+04	1.65457E+00	-2.56529E+04
1.4000E-02	1.64493E+04	1.78024E+00	-2.50734E+04
1.4400E-02	1.64493E+04	1.90590E+00	-2.40229E+04
1.4800E-02	1.64493E+04	2.03156E+00	-2.25442E+04
1.5200E-02	1.64493E+04	2.15723E+00	-2.06930E+04
1.5600E-02	1.64493E+04	2.28289E+00	-1.85317E+04
1.6000E-02	1.64493E+04	2.40855E+00	-1.61235E+04
1.6400E-02	1.64493E+04	2.53422E+00	-1.35279E+04
1.6800E-02	1.64493E+04	2.65988E+00	-1.07972E+04
1.7200E-02	1.64493E+04	2.78555E+00	-7.97515E+03
1.7600E-02	1.64493E+04	2.91121E+00	-5.09725E+03
1.8000E-02	1.64493E+04	3.03687E+00	-2.19170E+03
1.8400E-02	1.64493E+04	3.16254E+00	7.18385E+02
1.8800E-02	1.64493E+04	3.28820E+00	3.61244E+03
1.9200E-02	1.64493E+04	3.41386E+00	6.46982E+03
1.9600E-02	1.64493E+04	3.53953E+00	9.26717E+03
2.0000E-02	1.64493E+04	3.66519E+00	1.19763E+04

SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE

REQUEST NUMBER 4

TIME	MAGNITUDE OF THE LINEAR ACCELERATION OF MARKER 9 RELATIVE TO MARKER 1	ANGLE (RADIANS)
0.0000E+00	1.66457E+04	3.14159E+00
4.0000E-04	1.46284E+04	3.14159E+00
8.0000E-04	1.23198E+04	3.14159E+00
1.2000E-03	9.80171E+03	3.14159E+00
1.6000E-03	7.16251E+03	3.14159E+00
2.0000E-03	4.49292E+03	3.14159E+00
2.4000E-03	1.88067E+03	3.14159E+00
2.8000E-03	5.94835E+02	0.00000E+00
3.2000E-03	2.86758E+03	0.00000E+00
3.6000E-03	4.88881E+03	0.00000E+00
4.0000E-03	6.62928E+03	0.00000E+00
4.4000E-03	8.07936E+03	0.00000E+00
4.8000E-03	9.24729E+03	0.00000E+00
5.2000E-03	1.01558E+04	0.00000E+00
5.6000E-03	1.08377E+04	0.00000E+00
6.0000E-03	1.13316E+04	0.00000E+00
6.4000E-03	1.16778E+04	0.00000E+00
6.8000E-03	1.19142E+04	0.00000E+00
7.2000E-03	1.20748E+04	0.00000E+00
7.6000E-03	1.21870E+04	0.00000E+00
8.0000E-03	1.22709E+04	0.00000E+00
8.4000E-03	1.23386E+04	0.00000E+00
8.8000E-03	1.23939E+04	0.00000E+00
9.2000E-03	1.24318E+04	0.00000E+00
9.6000E-03	1.24386E+04	0.00000E+00
1.0000E-02	1.23919E+04	0.00000E+00
1.0400E-02	1.22611E+04	0.00000E+00
1.0800E-02	1.20084E+04	0.00000E+00
1.1200E-02	1.15907E+04	0.00000E+00
1.1600E-02	1.09629E+04	0.00000E+00
1.2000E-02	1.00814E+04	0.00000E+00
1.2400E-02	8.90979E+03	0.00000E+00
1.2800E-02	7.42376E+03	0.00000E+00
1.3200E-02	5.61627E+03	0.00000E+00
1.3600E-02	3.50119E+03	0.00000E+00
1.4000E-02	1.11485E+03	0.00000E+00
1.4400E-02	1.48490E+03	3.14159E+00
1.4800E-02	4.22205E+03	3.14159E+00
1.5200E-02	7.00758E+03	3.14159E+00
1.5600E-02	9.74564E+03	3.14159E+00
1.6000E-02	1.23398E+04	3.14159E+00
1.6400E-02	1.46985E+04	3.14159E+00
1.6800E-02	1.67398E+04	3.14159E+00
1.7200E-02	1.83944E+04	3.14159E+00
1.7600E-02	1.96077E+04	3.14159E+00
1.8000E-02	2.03415E+04	3.14159E+00
1.8400E-02	2.05741E+04	3.14159E+00
1.8800E-02	2.03006E+04	3.14159E+00
1.9200E-02	1.95332E+04	3.14159E+00
1.9600E-02	1.83002E+04	3.14159E+00
2.0000E-02	1.66457E+04	3.14159E+00

SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE

REQUEST NUMBER 5

TIME	MAGNITUDE OF THE FORCE EXERBY MARKER 7	8 (RADIANS)
0.0000E+00	7.75452E+02	2.97253E+00
4.0000E-04	6.87534E+02	2.91802E+00
8.0000E-04	5.86013E+02	2.85968E+00
1.2000E-03	4.74204E+02	2.79234E+00
1.6000E-03	3.56285E+02	2.70346E+00
2.0000E-03	2.37924E+02	2.55592E+00
2.4000E-03	1.30632E+02	2.19723E+00
2.8000E-03	8.61054E+01	1.10420E+00
3.2000E-03	1.52222E+02	3.17638E-01
3.6000E-03	2.39622E+02	8.46197E-02
4.0000E-03	3.19857E+02	6.27373E+00
4.4000E-03	3.87963E+02	6.22895E+00
4.8000E-03	4.43046E+02	6.20815E+00
5.2000E-03	4.85738E+02	6.20153E+00
5.6000E-03	5.17495E+02	6.20432E+00
6.0000E-03	5.40196E+02	6.21381E+00
6.4000E-03	5.55858E+02	6.22823E+00
6.8000E-03	5.66420E+02	6.24632E+00
7.2000E-03	5.73590E+02	6.26708E+00
7.6000E-03	5.78753E+02	6.52998E-03
8.0000E-03	5.82917E+02	3.03753E-02
8.4000E-03	5.86686E+02	5.48345E-02
8.8000E-03	5.90237E+02	7.93511E-02
9.2000E-03	5.93312E+02	1.03367E-01
9.6000E-03	5.95201E+02	1.26285E-01
1.0000E-02	5.94738E+02	1.47431E-01
1.0400E-02	5.90309E+02	1.66021E-01
1.0800E-02	5.79904E+02	1.81103E-01
1.1200E-02	5.61222E+02	1.91478E-01
1.1600E-02	5.31852E+02	1.95530E-01
1.2000E-02	4.89544E+02	1.90853E-01
1.2400E-02	4.32561E+02	1.73355E-01
1.2800E-02	3.60118E+02	1.34784E-01
1.3200E-02	2.73056E+02	5.43936E-02
1.3600E-02	1.75833E+02	6.14363E+00
1.4000E-02	9.19846E+01	5.46624E+00
1.4400E-02	1.24266E+02	4.22544E+00
1.4800E-02	2.38202E+02	3.81868E+00
1.5200E-02	3.64094E+02	3.66464E+00
1.5600E-02	4.87993E+02	3.57455E+00
1.6000E-02	6.03651E+02	3.50694E+00
1.6400E-02	7.06709E+02	3.44849E+00
1.6800E-02	7.93915E+02	3.39389E+00
1.7200E-02	8.62923E+02	3.34081E+00
1.7600E-02	9.12164E+02	3.28820E+00
1.8000E-02	9.40720E+02	3.23567E+00
1.8400E-02	9.48211E+02	3.18311E+00
1.8800E-02	9.34714E+02	3.13056E+00
1.9200E-02	9.00725E+02	3.07807E+00
1.9600E-02	8.47169E+02	3.02553E+00
2.0000E-02	7.75452E+02	2.97253E+00

7.3 EXAMPLE:

In the slider crank mechanism, a spring and damper are attached to the crank and the connecting rod which act in parallel. Calculate the velocity and acceleration of the slider, the force exerted by the slider on the connecting rod, and also the force produced by the spring and damper on the crank and connecting rod. Consider the length of the crank =2 inches, the length of the connecting rod =5 inches, the length of the slider =1 inch, the unstretched length of the spring =1.5 inches, the spring constant =5 lb/inch, damping coefficient =2.5 lb-s/inch, the weight of the crank =0.25 lb, weight of the connecting rod =1 lb, the weight of the slider =1.5 lb, the mass moment of inertia of the crank =0.08333 lb-sq.inch, the mass moment of inertia of the connecting rod =2.08333 lb-sq.inch, and the mass moment of inertia of the slider =0.125 lb-sq.inch. Initially, the crank is at 45 degrees (ccw). The crank is rotating at 36000 degrees/sec (ccw). Also consider theta 3 =16.429913 degrees (cw) and the translational length =1.5 inches (see fig.7.8). The spring is attached to the crank at a distance 0.5 inch from its rotational pin point with the ground. The other end of spring is attached to the connecting rod at a distance 3.7500061 inches from its rotational pin point with the slider The center of rotation of the crank and the center of the slider are in the same straight line. Angles and angular velocities measured in the clockwise directions are negative. Lbm units are being used and gc value is 386.088 .

SLIDER CRANK

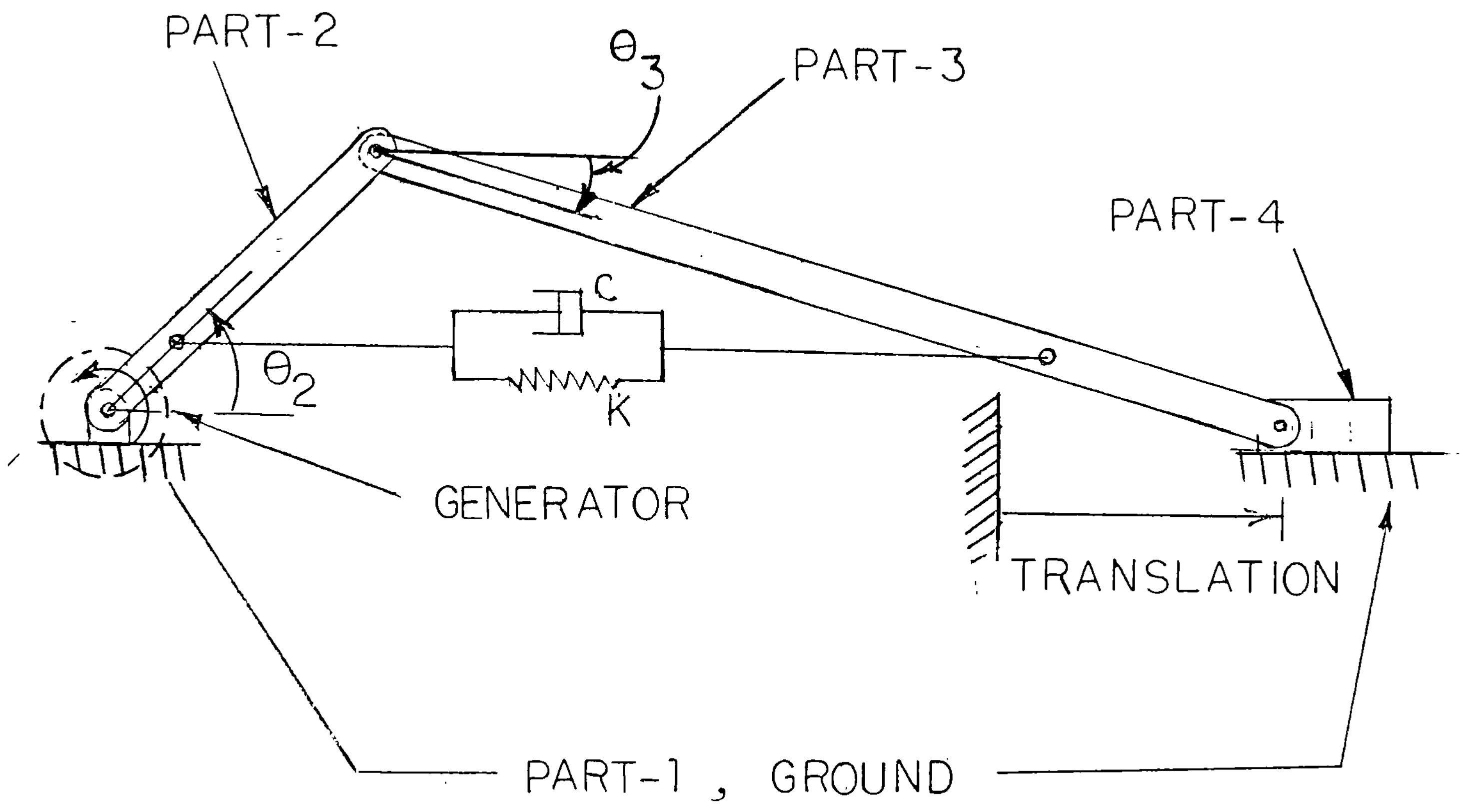


FIG. 7.7 - POSITION

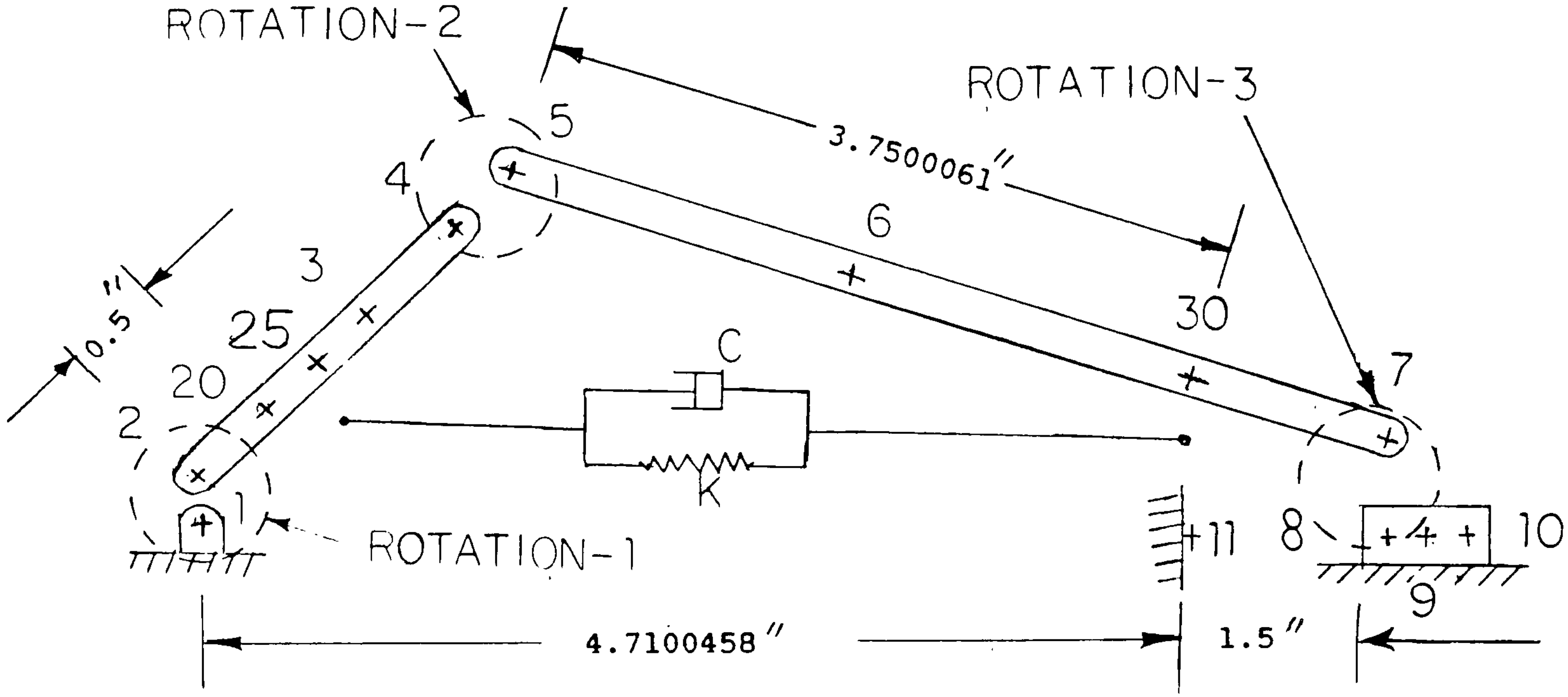


FIG. 7.8 - MARKERS

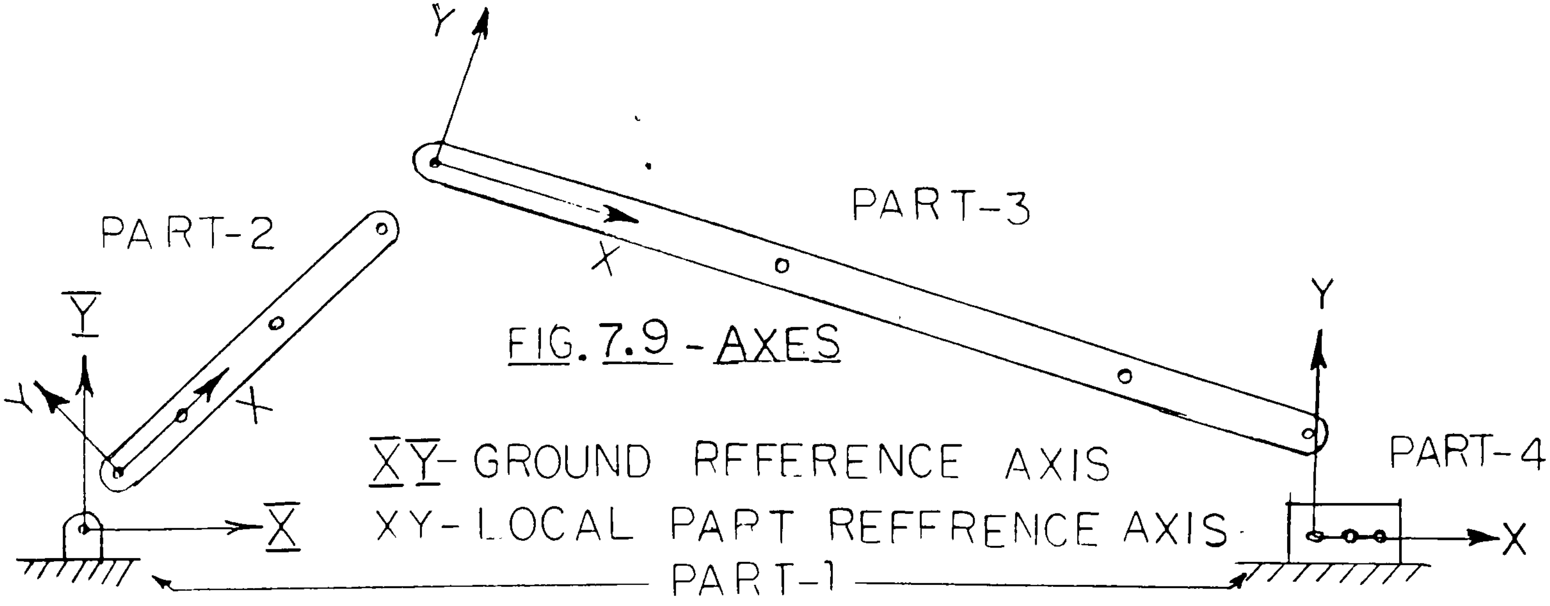


FIG. 7.9 - AXES

```
SLIDER CRANK MECHANISM WITH SPRING AND DAMPER
LIST

PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/11,GMARKER,PART=1,X=4.7100458,Y=0,ANGLE=0

PART/2,MASS=0.25,CM=25,INERTIA=0.08333,ANGLE=45
,DEGDANGLE=36000
MARKER/2,GMARKER,PART=2,X=0,Y=0
MARKER/20,POINT,PART=2,X=0.5,Y=0
MARKER/25,POINT,PART=2,X=1.0,Y=0
MARKER/3,POINT,PART=2,X=1.25,Y=0
MARKER/4,POINT,PART=2,X=2.0,Y=0

PART/3,MASS=1,CM=6,INERTIA=2.083333,ANGLE=-16.429913
MARKER/5,GMARKER,PART=3,X=0,Y=0,ANGLE=0
MARKER/30,POINT,PART=3,X=3.7500061,Y=0
MARKER/6,POINT,PART=3,X=1.8750031,Y=0
MARKER/7,POINT,PART=3,X=5,Y=0

PART/4,MASS=1.5,CM=9,INERTIA=0.125,ANGLE=0
MARKER/8,GMARKER,PART=4,X=0,Y=0,ANGLE=0
MARKER/9,POINT,PART=4,X=0.5,Y=0
MARKER/10,POINT,PART=4,X=1,Y=0

ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=7,J=8
TRANSLATION/1,I=8,J=11,TRANSLATION=1.5

FIELD/1,TRANSLATIONAL,SPRING,I=20,J=30
FIELD/1,PAR=5.0,1.5
      THE FIELD STATEMENT IS CONTINUED ON THE NEXT LINE BY TYPING
      "FIELD/1" IN THE BEGINNING OF LINE. THE OTHER OPTION WOULD BE
      TO TYPE A COMMA (,) IN THE FIRST COLUMN AND OMIT "FIELD/1".
      # 1 IS THE IDENTIFICATION NUMBER OF THE FIELD STATEMENT.
      THERE IS A TRANSLATIONAL SPRING BETWEEN  MARKERS I=20 &
      J=30. IN THE PARAMETER STATEMENT THE FIRST VALUE MUST BE A
      SPRING CONSTANT FOLLOWED BY THE SPRING LENGTH. THE CHANGE OF
      SEQUENCE OF THE PARAMETER VALUES IS NOT ALLOWED BY DRAM.
FIELD/2,TRANSLATIONAL,DAMPER,I=20,J=30,PAR=2.5
      # 2 IS THE IDENTIFICATION NUMBER OF THE FIELD STATEMENT.
      THERE IS A TRANSLATIONAL DAMPER BETWEEN MARKERS I=20 &
      J=30. IN THE PARAMETER STATEMENT THE ASSIGNED VALUE IS THE
      DAMPING COEFFICIENT.

GENERATOR/1,ROTATIONAL,ON=2,CONSTANT VELOCITY,DEGPAR=36000,PAR=45.0D

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.01,STEPS=50,NOPLOT,RANGLE

REQUEST/1,VELOCITY,I=8,J=11

REQUEST/2,FORCE,I=7,J=8

REQUEST/3,FORCE,I=20,J=30

REQUEST/4,ACCELERATION,I=8,J=11
```

**** NOTE ****

SOME OF THE OUTPUTS ARE NOT ENCLOSED DUE TO THE LIMITED AMOUNT OF SPACE AVAILABILITY.

END

OUTPUTS

Output comments are the same as example 7.2 .

```
-- DEFAULT VALUE (TSM1) -- SYSTEM/TS= 2.0000E-04

SYSTEM HAS    0 DEGREE(S) OF FREEDOM
SYSTEM WILL BE SIMULATED IN KINEMATIC MODE


*---- INPUT DATA LOOP CLOSURE CHECK  ----*
I---------------------------------------I
I ROTATION I DISPLACEMENT I   VELOCITY   I
I          I    ERROR     I    ERROR     I
I----------I--------------I--------------I
I        3 I  2.27625D-06 I  1.15060D+03 I
I----------I--------------I--------------I

LOOP CLOSURE DISPLACEMENT SOLUTION

CONVERGENCE WITHIN   0.00000D+00 IN  3 ITERATIONS

LOOP CLOSURE VELOCITY SOLUTION


CORRECTED INITIAL CONDITIONS


PART/     1     0.000000000000000D+00 DEG    0.000000000000000D+00 RAD/SEC
PART/     2     4.499999999999999D+01 DEG    6.283185307179586D+02 RAD/SEC
PART/     3    -1.642994018944455D+01 DEG   -1.852810265148533D+02 RAD/SEC
TRAN/     1     1.499999285685814D+00       -1.150603528179388D+03

KFLAG= 0 ORDER= 0 IFCT=    51 H= 0.20000D-03 ITER=    4


IN THE OUTPUT PHASE  1555 WORDS OF MEMORY WERE REQUIRED
```

SLIDER CRANK MECHANISM WITH SPRING AND DAMPER

REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 8 RELATIVE TO MARKER 11	ANGLE (RADIANS)	MAGNITUDE OF THE ANGULAR VELOCITY (RAD) OF MARKER 8 RELATIVE TO MARKER 11
0.0000E+00	1.15060E+03	3.14159E+00	0.00000E+00
2.0000E-04	1.24952E+03	3.14159E+00	0.00000E+00
4.0000E-04	1.31622E+03	3.14159E+00	0.00000E+00
6.0000E-04	1.35025E+03	3.14159E+00	0.00000E+00
8.0000E-04	1.35260E+03	3.14159E+00	0.00000E+00
1.0000E-03	1.32571E+03	3.14159E+00	0.00000E+00
1.2000E-03	1.27323E+03	3.14159E+00	0.00000E+00
1.4000E-03	1.19972E+03	3.14159E+00	0.00000E+00
1.6000E-03	1.11014E+03	3.14159E+00	0.00000E+00
1.8000E-03	1.00943E+03	3.14159E+00	0.00000E+00
2.0000E-03	9.02053E+02	3.14159E+00	0.00000E+00
2.2000E-03	7.91718E+02	3.14159E+00	0.00000E+00
2.4000E-03	6.81228E+02	3.14159E+00	0.00000E+00
2.6000E-03	5.72473E+02	3.14159E+00	0.00000E+00
2.8000E-03	4.66516E+02	3.14159E+00	0.00000E+00
3.0000E-03	3.63735E+02	3.14159E+00	0.00000E+00
3.2000E-03	2.63977E+02	3.14159E+00	0.00000E+00
3.4000E-03	1.66707E+02	3.14159E+00	0.00000E+00
3.6000E-03	7.11325E+01	3.14159E+00	0.00000E+00
3.8000E-03	2.36897E+01	0.00000E+00	0.00000E+00
4.0000E-03	1.18764E+02	0.00000E+00	0.00000E+00
4.2000E-03	2.15076E+02	0.00000E+00	0.00000E+00
4.4000E-03	3.13504E+02	0.00000E+00	0.00000E+00
4.6000E-03	4.14728E+02	0.00000E+00	0.00000E+00
4.8000E-03	5.19107E+02	0.00000E+00	0.00000E+00
5.0000E-03	6.26550E+02	0.00000E+00	0.00000E+00
5.2000E-03	7.36354E+02	0.00000E+00	0.00000E+00
5.4000E-03	8.47058E+02	0.00000E+00	0.00000E+00
5.6000E-03	9.56323E+02	0.00000E+00	0.00000E+00
5.8000E-03	1.06088E+03	0.00000E+00	0.00000E+00
6.0000E-03	1.15662E+03	0.00000E+00	0.00000E+00
6.2000E-03	1.23880E+03	0.00000E+00	0.00000E+00
6.4000E-03	1.30240E+03	0.00000E+00	0.00000E+00
6.6000E-03	1.34261E+03	0.00000E+00	0.00000E+00
6.8000E-03	1.35526E+03	0.00000E+00	0.00000E+00
7.0000E-03	1.33729E+03	0.00000E+00	0.00000E+00
7.2000E-03	1.28696E+03	0.00000E+00	0.00000E+00
7.4000E-03	1.20401E+03	0.00000E+00	0.00000E+00
7.6000E-03	1.08958E+03	0.00000E+00	0.00000E+00
7.8000E-03	9.46153E+02	0.00000E+00	0.00000E+00
8.0000E-03	7.77267E+02	0.00000E+00	0.00000E+00
8.2000E-03	5.87364E+02	0.00000E+00	0.00000E+00
8.4000E-03	3.81547E+02	0.00000E+00	0.00000E+00
8.6000E-03	1.65387E+02	0.00000E+00	0.00000E+00
8.8000E-03	5.52542E+01	3.14159E+00	0.00000E+00
9.0000E-03	2.74398E+02	3.14159E+00	0.00000E+00
9.2000E-03	4.86105E+02	3.14159E+00	0.00000E+00
9.4000E-03	6.84637E+02	3.14159E+00	0.00000E+00
9.6000E-03	8.64633E+02	3.14159E+00	0.00000E+00
9.8000E-03	1.02130E+03	3.14159E+00	0.00000E+00
1.0000E-02	1.15060E+03	3.14159E+00	0.00000E+00

SLIDER CRANK MECHANISM WITH SPRING AND DAMPER

REQUEST NUMBER 2

TIME	MAGNITUDE OF THE FORCE EXERBY MARKER 8 7	(RADIANS)
0.0000E+00	2.68881E+03	5.68685E+00
2.0000E-04	2.20619E+03	5.53197E+00
4.0000E-04	1.71572E+03	5.31853E+00
6.0000E-04	1.28278E+03	4.98686E+00
8.0000E-04	1.03132E+03	4.46917E+00
1.0000E-03	1.07564E+03	3.89519E+00
1.2000E-03	1.32519E+03	3.50334E+00
1.4000E-03	1.61623E+03	3.28156E+00
1.6000E-03	1.86385E+03	3.15428E+00
1.8000E-03	2.03850E+03	3.07891E+00
2.0000E-03	2.13742E+03	3.03455E+00
2.2000E-03	2.17109E+03	3.01029E+00
2.4000E-03	2.15578E+03	2.99992E+00
2.6000E-03	2.10885E+03	2.99981E+00
2.8000E-03	2.04597E+03	3.00784E+00
3.0000E-03	1.97994E+03	3.02295E+00
3.2000E-03	1.92046E+03	3.04481E+00
3.4000E-03	1.87453E+03	3.07358E+00
3.6000E-03	1.84703E+03	3.10956E+00
3.8000E-03	1.84128E+03	3.15291E+00
4.0000E-03	1.85937E+03	3.20338E+00
4.2000E-03	1.90222E+03	3.26007E+00
4.4000E-03	1.96918E+03	3.32146E+00
4.6000E-03	2.05735E+03	3.38551E+00
4.8000E-03	2.16051E+03	3.45001E+00
5.0000E-03	2.26802E+03	3.51288E+00
5.2000E-03	2.36394E+03	3.57249E+00
5.4000E-03	2.42697E+03	3.62790E+00
5.6000E-03	2.43167E+03	3.67902E+00
5.8000E-03	2.35146E+03	3.72692E+00
6.0000E-03	2.16323E+03	3.77457E+00
6.2000E-03	1.85310E+03	3.82910E+00
6.4000E-03	1.42256E+03	3.90979E+00
6.6000E-03	8.99215E+02	4.08845E+00
6.8000E-03	4.26304E+02	4.81510E+00
7.0000E-03	6.68055E+02	6.12884E+00
7.2000E-03	1.31151E+03	1.53610E-01
7.4000E-03	1.97623E+03	2.32495E-01
7.6000E-03	2.59384E+03	2.48211E-01
7.8000E-03	3.13301E+03	2.35467E-01
8.0000E-03	3.57575E+03	2.05618E-01
8.2000E-03	3.91312E+03	1.63456E-01
8.4000E-03	4.14286E+03	1.11367E-01
8.6000E-03	4.26732E+03	5.06980E-02
8.8000E-03	4.29163E+03	6.26548E+00
9.0000E-03	4.22214E+03	6.18990E+00
9.2000E-03	4.06530E+03	6.10740E+00
9.4000E-03	3.82708E+03	6.01784E+00
9.6000E-03	3.51322E+03	5.92022E+00
9.8000E-03	3.13042E+03	5.81189E+00
1.0000E-02	2.68881E+03	5.68685E+00

SLIDER CRANK MECHANISM WITH SPRING AND DAMPER

REQUEST NUMBER 4

TIME	MAGNITUDE OF THE LINEAR ACCELERATION OF MARKER 8 RELATIVE TO MARKER 11	ANGLE (RADIANS)	MAGNITUDE OF THE ANGULAR ACCELERATION (RADS) OF MARKER 8 RELATIVE TO MARKER 11
0.0000E+00	5.72625E+05	3.14159E+00	0.00000E+00
2.0000E-04	4.15024E+05	3.14159E+00	0.00000E+00
4.0000E-04	2.51586E+05	3.14159E+00	0.00000E+00
6.0000E-04	8.94900E+04	3.14159E+00	0.00000E+00
8.0000E-04	6.39278E+04	0.00000E+00	0.00000E+00
1.0000E-03	2.01897E+05	0.00000E+00	0.00000E+00
1.2000E-03	3.19018E+05	0.00000E+00	0.00000E+00
1.4000E-03	4.11937E+05	0.00000E+00	0.00000E+00
1.6000E-03	4.79700E+05	0.00000E+00	0.00000E+00
1.8000E-03	5.23663E+05	0.00000E+00	0.00000E+00
2.0000E-03	5.47005E+05	0.00000E+00	0.00000E+00
2.2000E-03	5.54010E+05	0.00000E+00	0.00000E+00
2.4000E-03	5.49322E+05	0.00000E+00	0.00000E+00
2.6000E-03	5.37354E+05	0.00000E+00	0.00000E+00
2.8000E-03	5.21913E+05	0.00000E+00	0.00000E+00
3.0000E-03	5.06038E+05	0.00000E+00	0.00000E+00
3.2000E-03	4.91998E+05	0.00000E+00	0.00000E+00
3.4000E-03	4.81373E+05	0.00000E+00	0.00000E+00
3.6000E-03	4.75167E+05	0.00000E+00	0.00000E+00
3.8000E-03	4.73900E+05	0.00000E+00	0.00000E+00
4.0000E-03	4.77675E+05	0.00000E+00	0.00000E+00
4.2000E-03	4.86184E+05	0.00000E+00	0.00000E+00
4.4000E-03	4.98675E+05	0.00000E+00	0.00000E+00
4.6000E-03	5.13871E+05	0.00000E+00	0.00000E+00
4.8000E-03	5.29859E+05	0.00000E+00	0.00000E+00
5.0000E-03	5.43993E+05	0.00000E+00	0.00000E+00
5.2000E-03	5.52840E+05	0.00000E+00	0.00000E+00
5.4000E-03	5.52260E+05	0.00000E+00	0.00000E+00
5.6000E-03	5.37661E+05	0.00000E+00	0.00000E+00
5.8000E-03	5.04493E+05	0.00000E+00	0.00000E+00
6.0000E-03	4.48929E+05	0.00000E+00	0.00000E+00
6.2000E-03	3.68620E+05	0.00000E+00	0.00000E+00
6.4000E-03	2.63327E+05	0.00000E+00	0.00000E+00
6.6000E-03	1.35222E+05	0.00000E+00	0.00000E+00
6.8000E-03	1.12504E+04	3.14159E+00	0.00000E+00
7.0000E-03	1.69908E+05	3.14159E+00	0.00000E+00
7.2000E-03	3.33597E+05	3.14159E+00	0.00000E+00
7.4000E-03	4.94980E+05	3.14159E+00	0.00000E+00
7.6000E-03	6.47174E+05	3.14159E+00	0.00000E+00
7.8000E-03	7.84160E+05	3.14159E+00	0.00000E+00
8.0000E-03	9.00983E+05	3.14159E+00	0.00000E+00
8.2000E-03	9.93782E+05	3.14159E+00	0.00000E+00
8.4000E-03	1.05973E+06	3.14159E+00	0.00000E+00
8.6000E-03	1.09696E+06	3.14159E+00	0.00000E+00
8.8000E-03	1.10446E+06	3.14159E+00	0.00000E+00
9.0000E-03	1.08202E+06	3.14159E+00	0.00000E+00
9.2000E-03	1.03025E+06	3.14159E+00	0.00000E+00
9.4000E-03	9.50585E+05	3.14159E+00	0.00000E+00
9.6000E-03	8.45359E+05	3.14159E+00	0.00000E+00
9.8000E-03	7.17904E+05	3.14159E+00	0.00000E+00
1.0000E-02	5.72625E+05	3.14159E+00	0.00000E+00

7.4 EXAMPLE:

In the slider crank mechanism, the crank is rotating at a velocity of 628.3185 rad/sec (36000 degrees/sec)(ccw) with a constant acceleration of 3000 rad/sq.sec. Calculate the displacement, velocity and acceleration of the slider. Consider the length of the crank =2 inches, the length of the connecting rod =5 inches, the length of the slider =1 inch, the weight of the crank =0.25 lb, the weight of the connecting rod =1 lb, the weight of the slider =1.5 lb, mass moment of inertia of the crank =0.08333 lb-sq.inch, mass moment of inertia of the connecting rod =2.083333 lb-sq.inch, mass moment inertia of the slider =0.125 lb-sq.inch. Also consider theta 3 = 16.429913 degrees (cw), the theta 2=45 degrees (ccw) and the translational length =1.5 inches. The center of rotation of the crank and the center of the slider are in the same straight line. Clockwise directions are considered as the negative. This example explains how to use the GENSUB subroutine when a constant acceleration is desired. Consider x=xo+vo+(1/2)*a*(t**2) and v=vo+a*t (where * ==> multiplication, ** ==> square). Lbm unites are being used and gc value is 386.088 .

SLIDER CRANK

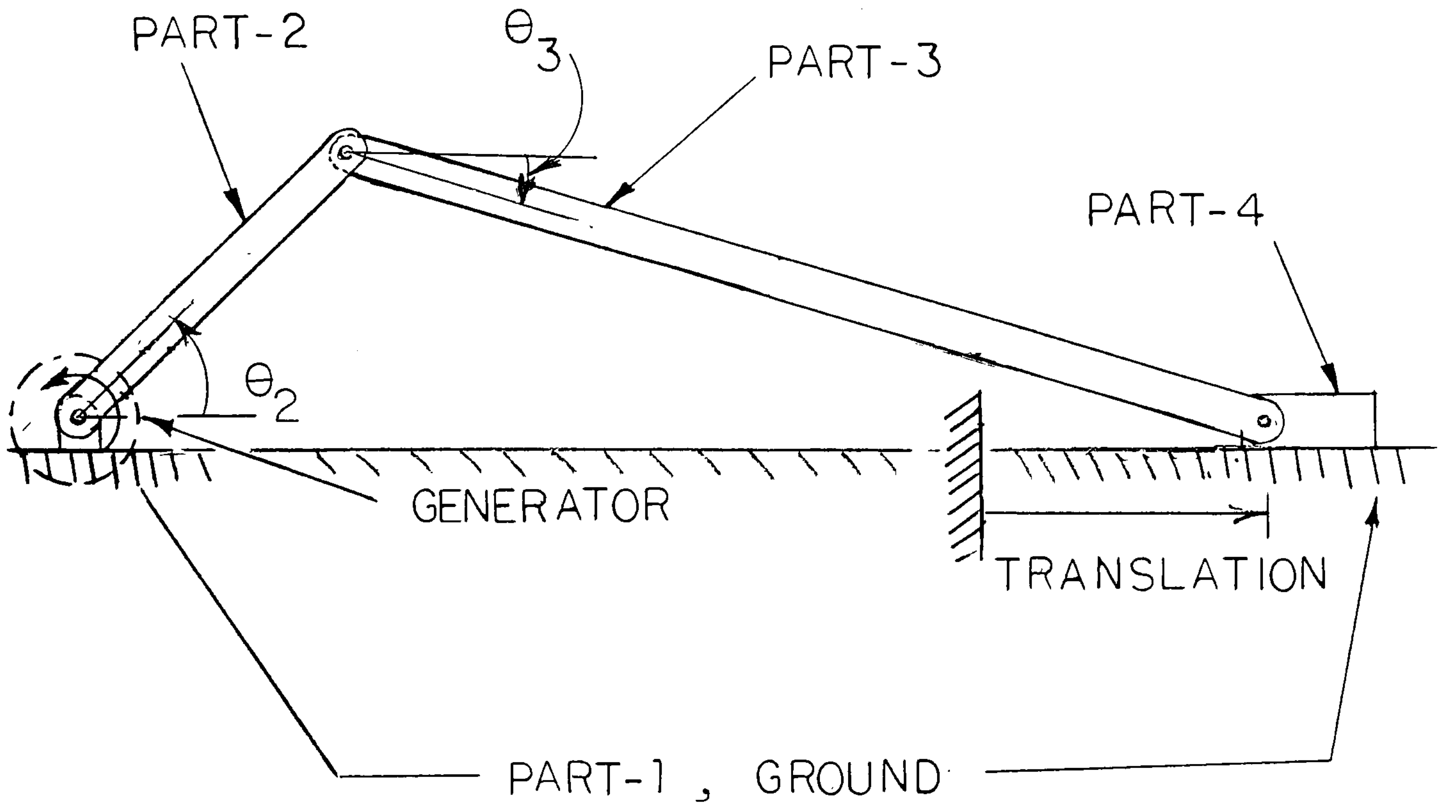


FIG. 7.10 - POSITION

SLIDER CRANK

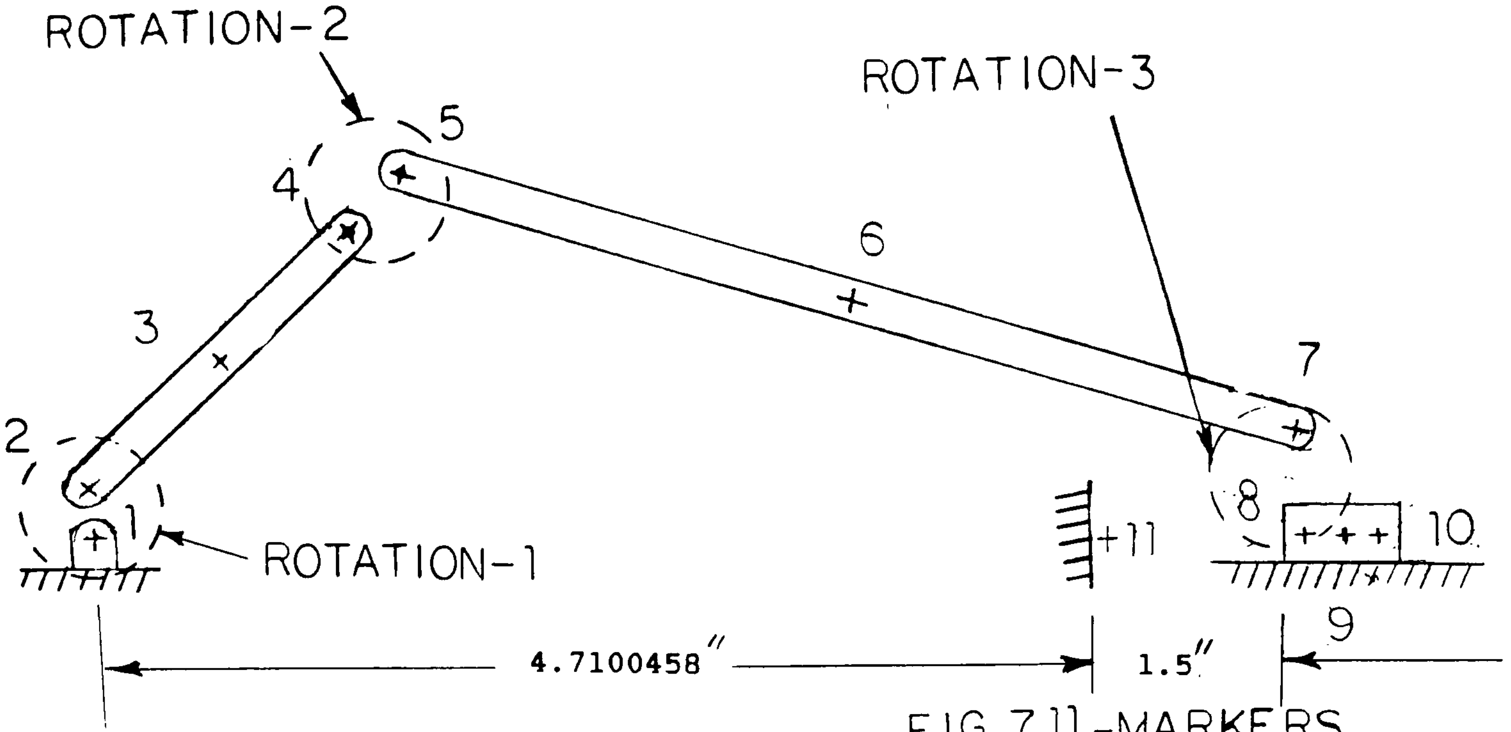


FIG. 7.11 - MARKERS

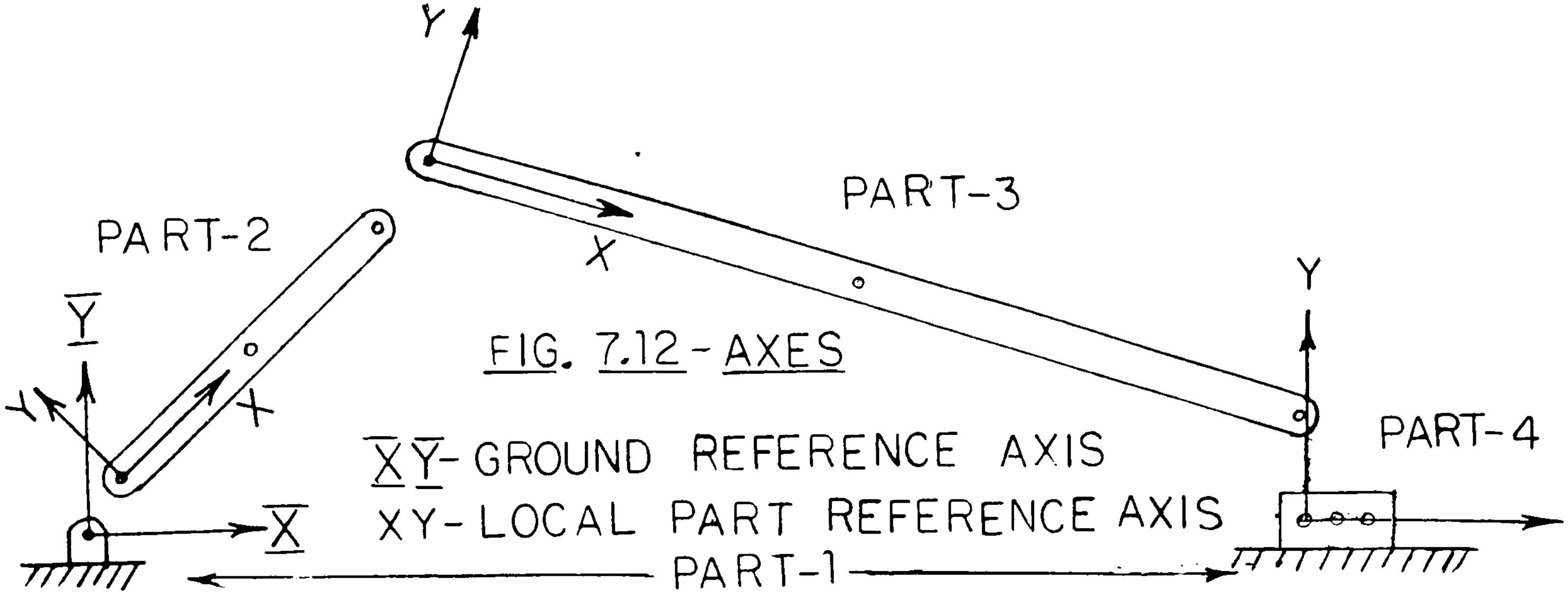


FIG. 7.12 - AXES

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SLIDER CRANK MECHANISM [CONSTANT ACCELERATION]
LIST

PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/11,GMARKER,PART=1,X=4.7100458,Y=0,ANGLE=0

PART/2,MASS=0.25,CM=3,INERTIA=0.08333,ANGLE=45
,DEGDANGLE=36000
MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/3,POINT,PART=2,X=1,Y=0
MARKER/4,POINT,PART=2,X=2.0,Y=0

PART/3,MASS=1,CM=6,INERTIA=2.083333,ANGLE=-16.429913
MARKER/5,GMARKER,PART=3,X=0,Y=0,ANGLE=0
MARKER/6,POINT,PART=3,X=2.5,Y=0
MARKER/7,POINT,PART=3,X=5,Y=0

PART/4,MASS=1.5,CM=9,INERTIA=0.125,ANGLE=0
MARKER/8,GMARKER,PART=4,X=0,Y=0,ANGLE=0
MARKER/9,POINT,PART=4,X=0.5,Y=0
MARKER/10,POINT,PART=4,X=1,Y=0

ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=7,J=8
TRANSLATION/1,I=8,J=11,TRANSLATION=1.5

GENERATOR/1,ROTATIONAL,INPUT,ON=2,PAR=(0.7853916,DEG=36000,3000.0)
      A GENERATOR INPUTs A ROTATIONAL MOTION TO A MECHANICAL SYSTEM.
      INPUT==> ALLOWS THE "GENSUB" SUBROUTINE TO BE LINKED TO DRAM.
      ON==> ROTATIONAL MOTION IS GENERATED ON PART 2.
      IN THE PARAMETER STATEMENT,ANGULAR DISPLACEMENT (THETA 2)=
      0.7853916 RADIANS, ANGULAR VELOCITY=36000 DEGREES/SEC,
      ANGULAR ACCELERATION=3000 RADIAN/SQ.SEC.
      PAR==> EXPLAINS HOW TO USE VALUES IN DEGREES THROUGH THE "PAR"
      STATEMENT.
SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.01,STEPS=50,NOPLOT,RANGLE

REQUEST/1,DISPLACEMENT,I=9,J=11

REQUEST/2,VELOCITY,I=9,J=11

REQUEST/3,ACCELERATION,I=9,J=11

       *** NOTE ***

       WHENEVER THERE ARE NO COMMENTS IN THE PROGRAM, THEN ASSUME
       THAT THOSE ARE EXACTLY SIMILAR TO THE PREVIOUS EXAMPLES OF
       THIS USER'S MANUAL.
       SOME OF THE OUTPUTS ARE NOT ENCLOSED DUE TO THE LIMITED AMOUNT
       OF SPACE AVAILABILITY.

END
```

```
* PROGRAM NAME  : SUBROUTINE GENSUB
*
* PROGRAMMER    : DEEPAK N. RODE
*
* DATE WRITTEN  : JUNE 7, 1986
*
* OBJECTIVE     : TO CALCULATE THE INPUT VELOCITY AT DIFFERENT TIME
*                 INTERVALS BY KEEPING THE ANGULAR ACCELERATION
*                 CONSTANT.
*
* DESCRIPTION OF PARAMETERS:
*
*               XO = INPUT DISPLACEMENT IN RADIANS.
*               VO = INPUT VELOCITY IN DEGREES/SEC.
*               AO = INPUT ACCELERATION RADIAN/SQ.SEC.
*                X = DISPLACEMENT (OUTPUT).
*               DX = FIRST TIME DERIVATIVE OF X [VELOCITY] (OUTPUT).
*              D2X= SECOND TIME DERIVATIVE OF X [ACCELERATION] (OUTPUT).
*             TIME= SIMULATION TIME IN SEC.
*              PAR= VALUES TO BE INPUT TO THE SUBROUTINE. THE MAXIMUM
*                   VALUES CAN BE 10.
*             NEGN= IDENTIFICATION NUMBER OF THE GENERATOR.
*
*
* Comments:
*
*               THIS SUBROUTINE PROVIDES A SPECIAL WAY TO  PASS THE
*               INPUT VALUES TO DRAM RATHER THAN USING DRAM'S STANDARD
*               FORM. (DRAM'S "STANDARD FORM" IS THAT FORM WHERE THERE
*               IS NO NEED TO USE ANY TYPE OF THE SUBROUTINE FOR THE
*               THE INPUT DATA CODING. THE INPUT DATA CAN BE CODED
*               THROUGH DRAM'S AVAILABLE STATEMENTS.) BY USING THIS KIND
*               OF SUBROUTINE,IT IS POSSIBLE TO USE THE DESIRED INPUT
*               VALUE TO THE GENERATOR IN ORDER TO SIMULATE THE MOTION
*               OF THE SYSTEM.
*               NGEN==> IT IS A GENERATOR NUMBER. THIS "NGEN" STATEMENT
*               BRANCHES THE GENERATOR INTO TWO OR MORE GENERATORS.
*               FOR EXAMPLE:
*                     IF (NGEN .EQ. 2) THEN GO TO 100.
*               100   DX=.....    [ THIS USES THE SECOND GENERATOR OF THE
*                                   SYSTEM.]
*                     ELSE GO TO 50
*                50   DX=.....    [ THIS USES THE FIRST GENERATOR OF THE
*                                   SYSTEM.]
*               NOTE: THE EQUATIONS OF DISPLACEMENT, VELOCITY AND
*               ACCELERATION CAN BE CODED IN  FORTRAN IV LANGUAGE EXCEPT
*               t ( TIME ) MUST BE CODED AS "TIME" INSTEAD OF
*               TYPING ONLY "T" LETTER. Refer to the following equations.
*
*


      SUBROUTINE GENSUB (TIME,PAR,NGEN,X,DX,D2X)
      IMPLICIT REAL*8 (A-H,O-Z)

      DIMENSION PAR(3)

      XO= PAR(1)
      VO= PAR(2)
      AO= PAR(3)
```

```
*
*       DISPLACEMENT OF CRANK
*

        X=X0+V0*TIME+(0.5D0)*A0*(TIME)**2

*
*       VELOCITY OF CRANK
*

        DX=V0+A0*(TIME)
*
*       CONSTANT CRANK ACCELERATION
*

        D2X=A0

        RETURN

        END
```

OUTPUTS

Output comments are the same as example 7.2

```
-- DEFAULT VALUE (TSM1) -- SYSTEM/TS= 2.0000E-04

SYSTEM HAS    0 DEGREE(S) OF FREEDOM
SYSTEM WILL BE SIMULATED IN KINEMATIC MODE


*---- INPUT DATA LOOP CLOSURE CHECK  ----*
I---------------------------------------I
I ROTATION I DISPLACEMENT I   VELOCITY  I
I          I    ERROR     I    ERROR    I
I----------I--------------I-------------I
I        3 I  1.15950D-05 I 6.48397D-03 I
I----------I--------------I-------------I


LOOP CLOSURE DISPLACEMENT SOLUTION

CONVERGENCE WITHIN   0.00000D+00 IN  3 ITERATIONS

LOOP CLOSURE VELOCITY SOLUTION


CORRECTED INITIAL CONDITIONS


PART/     1     0.000000000000000D+00 DEG     0.000000000000000D+00 RAD/SEC
PART/     2     4.499962394502694D+01 DEG     6.283185307179586D+02 RAD/SEC
PART/     3    -1.642982929655058D+01 DEG    -1.852821368377959D+02 RAD/SEC
TRAN/     1     1.500011304826205D+00        -1.150597546509802D+03

KFLAG= 0 ORDER= 0 IFCT=    51 H= 0.20000D-03 ITER=     4


IN THE OUTPUT PHASE  1395 WORDS OF MEMORY WERE REQUIRED
```

SLIDER CRANK MECHANISM [CONSTANT ACCELERATION]

REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR DISPLACEMENT OF MARKER 9 RELATIVE TO MARKER 11	ANGLE (RADIANS)
0.0000E+00	2.00001E+00	0.00000E+00
2.0000E-04	1.75935E+00	0.00000E+00
4.0000E-04	1.50185E+00	0.00000E+00
6.0000E-04	1.23401E+00	0.00000E+00
8.0000E-04	9.62305E-01	0.00000E+00
1.0000E-03	6.92916E-01	0.00000E+00
1.2000E-03	4.31420E-01	0.00000E+00
1.4000E-03	1.82580E-01	0.00000E+00
1.6000E-03	4.97991E-02	3.14159E+00
1.8000E-03	2.62920E-01	3.14159E+00
2.0000E-03	4.54944E-01	3.14159E+00
2.2000E-03	6.24867E-01	3.14159E+00
2.4000E-03	7.72352E-01	3.14159E+00
2.6000E-03	8.97536E-01	3.14159E+00
2.8000E-03	1.00086E+00	3.14159E+00
3.0000E-03	1.08289E+00	3.14159E+00
3.2000E-03	1.14422E+00	3.14159E+00
3.4000E-03	1.18537E+00	3.14159E+00
3.6000E-03	1.20669E+00	3.14159E+00
3.8000E-03	1.20836E+00	3.14159E+00
4.0000E-03	1.19034E+00	3.14159E+00
4.2000E-03	1.15238E+00	3.14159E+00
4.4000E-03	1.09403E+00	3.14159E+00
4.6000E-03	1.01467E+00	3.14159E+00
4.8000E-03	9.13595E-01	3.14159E+00
5.0000E-03	7.90069E-01	3.14159E+00
5.2000E-03	6.43488E-01	3.14159E+00
5.4000E-03	4.73530E-01	3.14159E+00
5.6000E-03	2.80354E-01	3.14159E+00
5.8000E-03	6.48123E-02	3.14159E+00
6.0000E-03	1.71342E-01	0.00000E+00
6.2000E-03	4.25299E-01	0.00000E+00
6.4000E-03	6.93117E-01	0.00000E+00
6.6000E-03	9.69743E-01	0.00000E+00
6.8000E-03	1.24916E+00	0.00000E+00
7.0000E-03	1.52464E+00	0.00000E+00
7.2000E-03	1.78902E+00	0.00000E+00
7.4000E-03	2.03507E+00	0.00000E+00
7.6000E-03	2.25584E+00	0.00000E+00
7.8000E-03	2.44493E+00	0.00000E+00
8.0000E-03	2.59677E+00	0.00000E+00
8.2000E-03	2.70683E+00	0.00000E+00
8.4000E-03	2.77177E+00	0.00000E+00
8.6000E-03	2.78956E+00	0.00000E+00
8.8000E-03	2.75956E+00	0.00000E+00
9.0000E-03	2.68251E+00	0.00000E+00
9.2000E-03	2.56056E+00	0.00000E+00
9.4000E-03	2.39719E+00	0.00000E+00
9.6000E-03	2.19710E+00	0.00000E+00
9.8000E-03	1.96608E+00	0.00000E+00
1.0000E-02	1.71077E+00	0.00000E+00

7.5 EXAMPLE:

Link 2 (crank) of the six-bar linkage mechanism is rotating at a constant velocity (w2)of 4000 rpm (24000 deg/sec)(ccw). Calculate the angular velocities and angular accelerations of this kinematic system. Lengths of the links (parts) are: r2 =1 inch, r3 =r4 =2 inches, r5 =r6 =2.5 inches; Weights of links (parts): w2 =0.15 lb, w3 =w4 =0.3 lb, w5 =w6 =0.35 lb; Mass moment of inertia of links (parts) are: I2 =0.0125 lb-sq.inch, I3 =I4 =0.1 lb-sq.inch, I5 =I6 =0.18229167 lb-sq.inch: Initial angular velocities of links (parts): w3 = 195 rad/sec cw (11172.667 degree/sec cw), w4 =37.84059 rad/sec ccw (2168.1061 degree/sec ccw), Initial angles of the links (parts) are: Theta 3 =35 degrees ccw, Theta 4 =71 degrees cw, Theta 5 =59 degrees ccw, Theta 6 =93 degrees cw. Initial angular velocities of links 3 and 4 need not necessarily be supplied, however. The initial position of link 2 (theta 2) is at 45 degrees. Angles and angular velocities measured in the clockwise direction are negative. GC will be taken as 386.088.

SIXBAR LINKAGE

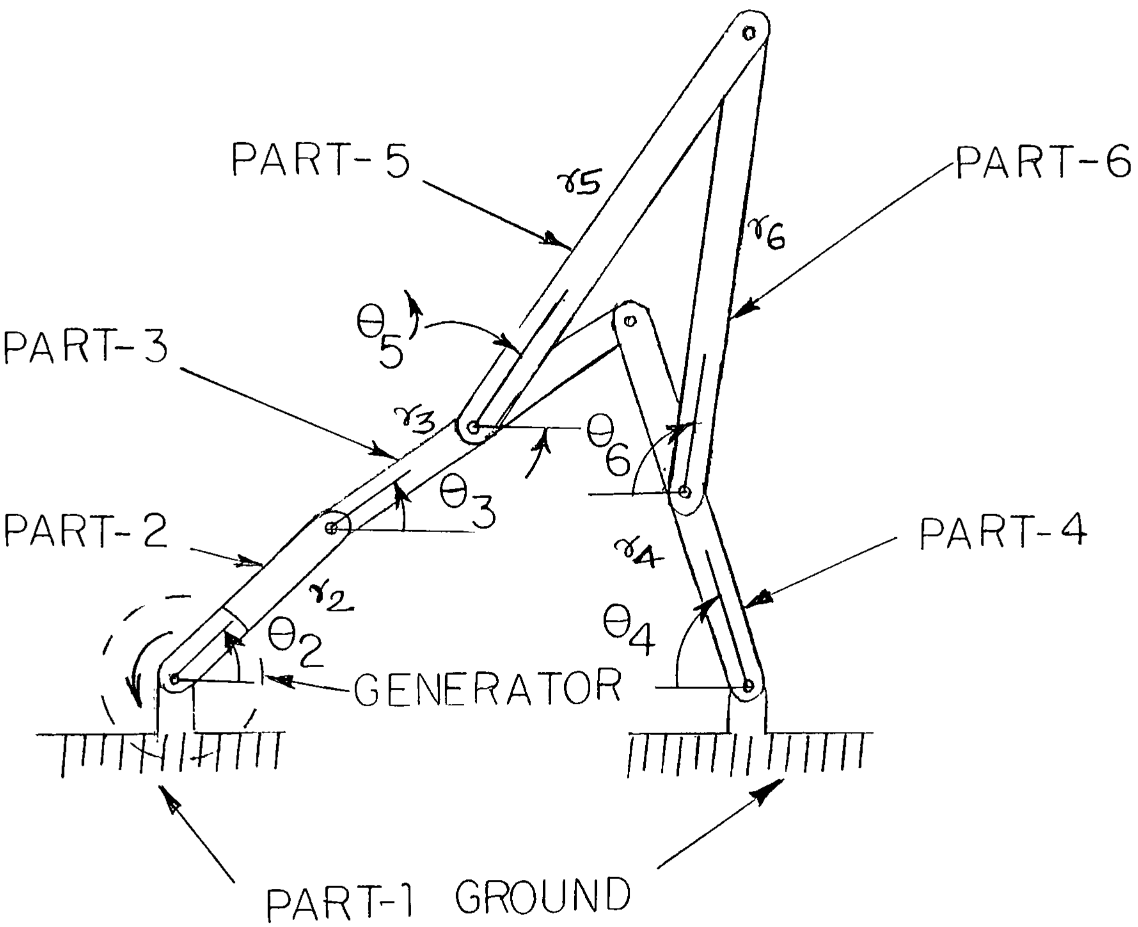


FIG. 7.13 - POSITION

SIXBAR LINKAGE

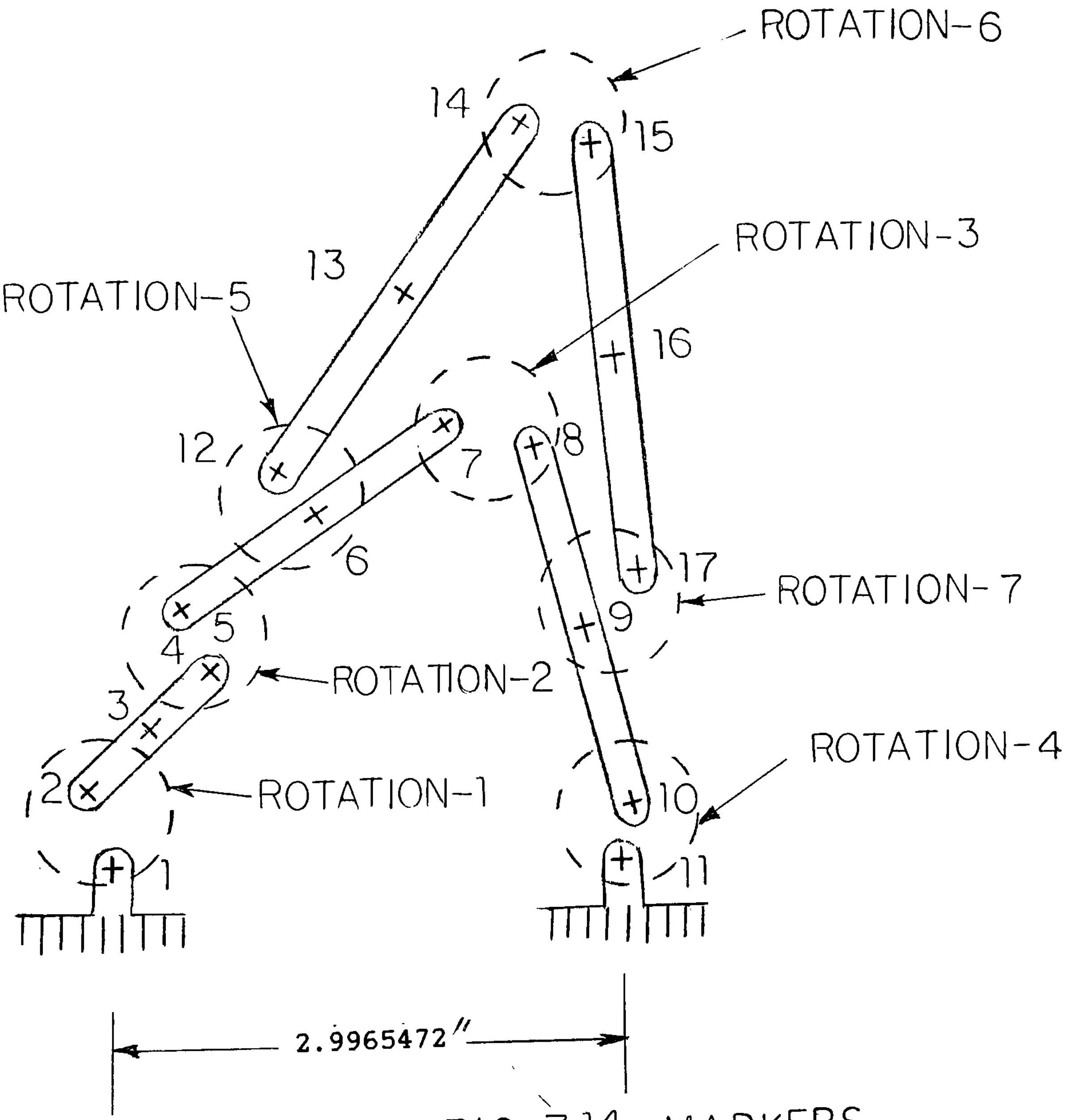
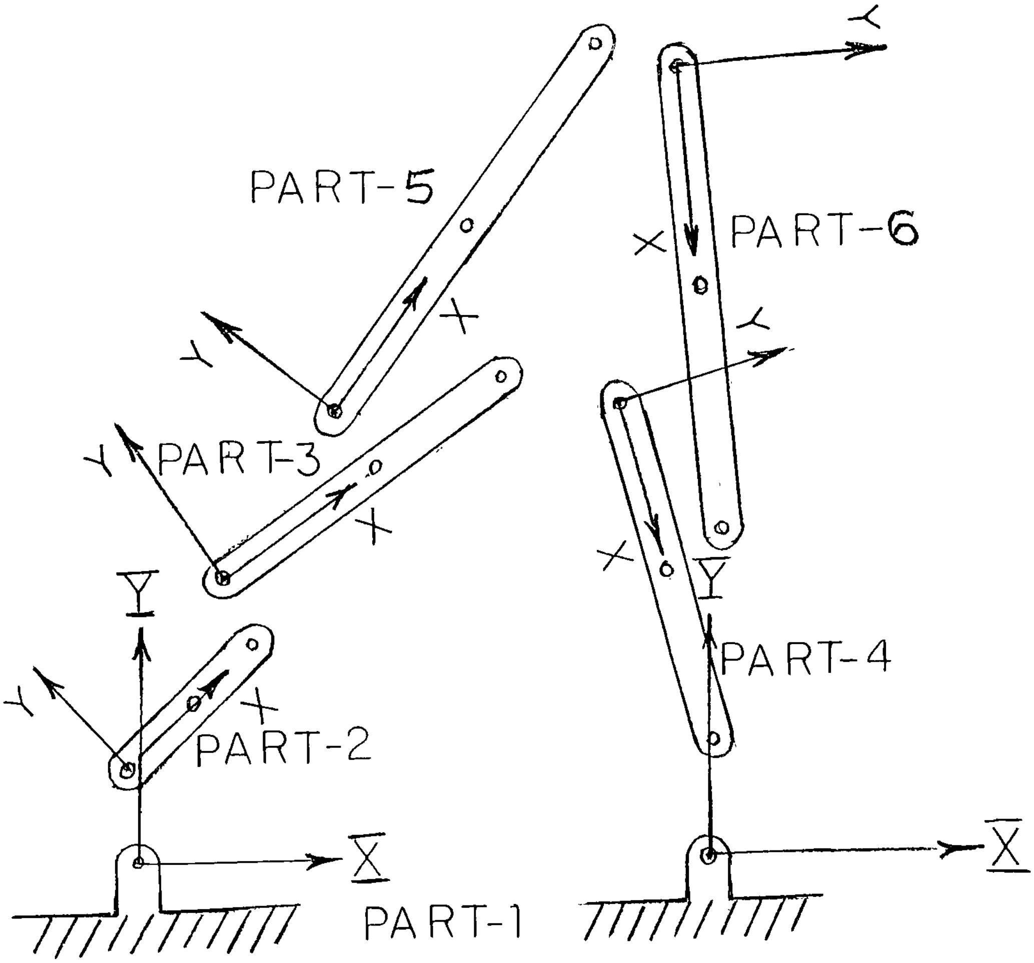


FIG. 7.14 - MARKERS

SIXBAR LINKAGE



$\overline{X}\,\overline{Y}$- GROUND REFERENCE AXIS

XY- LOCAL PART REFERENCE AXIS

FIG. 7.15- AXES

SIX-BAR LINKAGE MECHANISM [KINEMATIC ANALYSIS]

```
PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/11,POINT,PART=1,X=2.9965472,Y=0

PART/2,MASS=0.15,CM=3,INERTIA=0.0125,ANGLE=45
PART/2,DEGDANGLE=24000
MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/3,GMARKER,PART=2,X=.5,Y=0,ANGLE=0
MARKER/4,POINT,PART=2,X=1,Y=0

PART/3,MASS=0.3,CM=6,INERTIA=0.1,ANGLE=35
MARKER/5,POINT,PART=3,X=0,Y=0
MARKER/6,GMARKER,PART=3,X=1,Y=0,ANGLE=0
MARKER/7,POINT,PART=3,X=2,Y=0

PART/4,MASS=0.3,CM=9,INERTIA=0.1,ANGLE=-71
MARKER/8,POINT,PART=4,X=0,Y=0
MARKER/9,GMARKER,PART=4,X=1,Y=0,ANGLE=0
MARKER/10,POINT,PART=4,X=2,Y=0

PART/5,MASS=0.35,CM=13,INERTIA=0.1822917,ANGLE=59
MARKER/12,POINT,PART=5,X=0,Y=0
MARKER/13,GMARKER,PART=5,X=1.25,Y=0,ANGLE=0
MARKER/14,POINT,PART=5,X=2.5,Y=0

PART/6,MASS=0.35,CM=16,INERTIA=0.18229167,ANGLE=-93
MARKER/15,POINT,PART=6,X=0,Y=0
MARKER/16,GMARKER,PART=6,X=1.25,Y=0,ANGLE=0
MARKER/17,POINT,PART=6,X=2.5,Y=0

ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=7,J=8
ROTATION/4,I=10,J=11
ROTATION/5,I=6,J=12
ROTATION/6,I=14,J=15
ROTATION/7,I=17,J=9


GENERATOR/1,ROTATIONAL,ON=2,CONSTVEL,DEGPAR=24000,PAR=45.0D

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.015,STEPS=50,NOPLOT,RANGLE

REQUEST/1,DISPLACEMENT,I=14,J=6
REQUEST/2,DISPLACEMENT,I=15,J=9

REQUEST/3,VELOCITY,I=7,J=4
REQUEST/4,VELOCITY,I=6,J=1
REQUEST/5,VELOCITY,I=8,J=1
REQUEST/6,VELOCITY,I=9,J=1
REQUEST/7,VELOCITY,I=14,J=6
REQUEST/8,VELOCITY,I=13,J=1
REQUEST/9,VELOCITY,I=15,J=9
REQUEST/10,VELOCITY,I=16,J=1

REQUEST/11,ACCELERATION,I=5,J=1
```

```
REQUEST/12,ACCELERATION,I=6,J=1
REQUEST/13,ACCELERATION,I=8,J=1
REQUEST/14,ACCELERATION,I=9,J=1
REQUEST/15,ACCELERATION,I=8,J=4
REQUEST/16,ACCELERATION,I=14,J=6
REQUEST/17,ACCELERATION,I=13,J=1
REQUEST/18,ACCELERATION,I=16,J=1
REQUEST/19,ACCELERATION,I=15,J=9
```

*** NOTE ***

PARTS CAN BE DESCRIBED BY USING THE GMARKER ONLY (DONOT NEED TO HAVE POINT). DRAM ALLOWS GMARKER.

THIS PROBLEM CAN BE CONVERTED INTO THE FOUR-BAR LINKAGE MECHANISM BY DELETING THE FOLLOWING STATEMENTS:

1. DELETE COMPLETE DESCRIPTION OF PART 5, AND PART 6.
2. DELETE ROTATIONAL CONTACTS. THAT IS, ROTATION/5, ROTATION/6, AND ROTATION/7.
3. DELETE OUTPUT REQUESTS. THAT IS, REQUEST/1,REQUEST/2, REQUEST/7,REQUEST/8,REQUEST/9,REQUEST/10,REQUEST/16, REQUEST/17,REQUEST/18,AND REQUEST/19.

THE VALUES OF DEGDANGLE NEED NOT BE SPECIFIED FOR EACH PART EXCEPT PART 2 HOWEVER. PART 2 GENERATES THE MOTION OF THE SYSTEM.

THE COMMENTS OF THIS PROGRAM ARE EXACTLY SIMILAR TO THOSE OF THE FIRST TWO EXAMPLES OF THIS USER'S MANUAL.

SOME OF THE OUTPUTS ARE NOT ENCLOSED DUE TO THE LIMITED AMOUNT OF SPACE AVAILABILITY.

```
END
```

OUTPUTS

Output comments are the same as example 7.2 .

```
SIX BAR LINKAGE MECHANISM [ KINEMATIC ANALYSIS ]


-- DEFAULT VALUE (TSM1) -- SYSTEM/TS= 3.0000E-04

SYSTEM HAS   0 DEGREE(S) OF FREEDOM
SYSTEM WILL BE SIMULATED IN KINEMATIC MODE



*---- INPUT DATA LOOP CLOSURE CHECK  ----*
I---------------------------------------I
I ROTATION I DISPLACEMENT I   VELOCITY  I
I          I    ERROR     I    ERROR    I
I----------I--------------I-------------I
I        3 I  3.67775D-02 I  1.65479D+00 I
I        6 I  2.20626D-02 I  2.10253D+02 I
I----------I--------------I-------------I


LOOP CLOSURE DISPLACEMENT SOLUTION

CONVERGENCE WITHIN   6.03830D-17 IN  4 ITERATIONS

LOOP CLOSURE VELOCITY SOLUTION


CORRECTED INITIAL CONDITIONS


PART/     1     0.000000000000000D+00 DEG    0.000000000000000D+00 RAD/SEC
PART/     2     4.499999999999999D+01 DEG    4.188790204786391D+02 RAD/SEC
PART/     3     3.603539267937019D+01 DEG   -1.972771755679073D+02 RAD/SEC
PART/     4    -7.036259840914907D+01 DEG    3.401955325079225D+01 RAD/SEC
PART/     5     5.897257544946741D+01 DEG   -1.197810877723530D+02 RAD/SEC
PART/     6    -9.329978117924629D+01 DEG   -4.347653454476214D+01 RAD/SEC

KFLAG= 0 ORDER= 0 IFCT=    51 H= 0.30000D-03 ITER=     4

IN THE OUTPUT PHASE  3007 WORDS OF MEMORY WERE REQUIRED
```

REQUEST NUMBER 3

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 7 RELATIVE TO MARKER 4	ANGLE (RADIANS)
0.0000E+00	3.94554E+02	5.34132E+00
3.0000E-04	3.64843E+02	5.28437E+00
6.0000E-04	3.36078E+02	5.23182E+00
9.0000E-04	3.09306E+02	5.18345E+00
1.2000E-03	2.85023E+02	5.13891E+00
1.5000E-03	2.63375E+02	5.09781E+00
1.8000E-03	2.44301E+02	5.05977E+00
2.1000E-03	2.27633E+02	5.02440E+00
2.4000E-03	2.13151E+02	4.99137E+00
2.7000E-03	2.00621E+02	4.96036E+00
3.0000E-03	1.89812E+02	4.93109E+00
3.3000E-03	1.80493E+02	4.90334E+00
3.6000E-03	1.72432E+02	4.87688E+00
3.9000E-03	1.65355E+02	4.85156E+00
4.2000E-03	1.58868E+02	4.82725E+00
4.5000E-03	1.52203E+02	4.80391E+00
4.8000E-03	1.43308E+02	4.78169E+00
5.1000E-03	1.24239E+02	4.76138E+00
5.4000E-03	4.48334E+01	4.74706E+00
5.7000E-03	3.22442E+02	1.62238E+00
6.0000E-03	5.17952E+02	1.68973E+00
6.3000E-03	5.49075E+02	1.77038E+00
6.6000E-03	5.54192E+02	1.85327E+00
6.9000E-03	5.51802E+02	1.93628E+00
7.2000E-03	5.45543E+02	2.01862E+00
7.5000E-03	5.36358E+02	2.09980E+00
7.8000E-03	5.24446E+02	2.17939E+00
8.1000E-03	5.09714E+02	2.25699E+00
8.4000E-03	4.91915E+02	2.33215E+00
8.7000E-03	4.70684E+02	2.40439E+00
9.0000E-03	4.45559E+02	2.47316E+00
9.3000E-03	4.15981E+02	2.53784E+00
9.6000E-03	3.81298E+02	2.59770E+00
9.9000E-03	3.40783E+02	2.65194E+00
1.0200E-02	2.93667E+02	2.69961E+00
1.0500E-02	2.39208E+02	2.73967E+00
1.0800E-02	1.76819E+02	2.77097E+00
1.1100E-02	1.06273E+02	2.79231E+00
1.1400E-02	2.79959E+01	2.80247E+00
1.1700E-02	5.65625E+01	5.94198E+00
1.2000E-02	1.44565E+02	5.92692E+00
1.2300E-02	2.31625E+02	5.89866E+00
1.2600E-02	3.12094E+02	5.85776E+00
1.2900E-02	3.79983E+02	5.80566E+00
1.3200E-02	4.30374E+02	5.74464E+00
1.3500E-02	4.60769E+02	5.67755E+00
1.3800E-02	4.71672E+02	5.60739E+00
1.4100E-02	4.66121E+02	5.53688E+00
1.4400E-02	4.48515E+02	5.46816E+00
1.4700E-02	4.23382E+02	5.40270E+00
1.5000E-02	3.94554E+02	5.34132E+00

7.6 EXAMPLE:

The Stephenson's kinematic chain example has been chosen from the research paper "Analysis of The Angular Velocities and Acceleration in a Plane Linkage by Means of A Numerical Procedure". This paper was published in the "ASME" Journal of Mechanisms, Transmission, and Automation in Design, December 1983, vol. 105/627. The Stephenson's kinematic chain consists of six links. Link 1 is fixed to a ground. The input data of the Stephenson's kinematic chain is as follows: Length of links (See figure 7.17): r2 (crank) =1.6 inches, r3 =4.5 inches; Lengths of triangular link 4: r4 =4.5 inches, r4' =2.1 inches, r4" =3.2 inches; r5 =2.4 inches, r6 =4 inches; Length of triangular link 1: r1 = 4.8 inches, r1' =3.4 inches, r1" =1.8 inches. Angles (See figure 7.16): Theta 2 =150 degrees, theta 3 =60 degrees, theta 4 =45 degrees cw, theta 5 =-65 degrees, theta 6 =97 degrees cw. Angular velocity of link 2 =436.3 rad/sec (24998.149 degree/sec) (ccw). Calculate the angular velocities and angular acceleration of the given system. Angles measured in the clockwise direction are negative.

STEPHENSON'S KINEMATIC
CHAIN

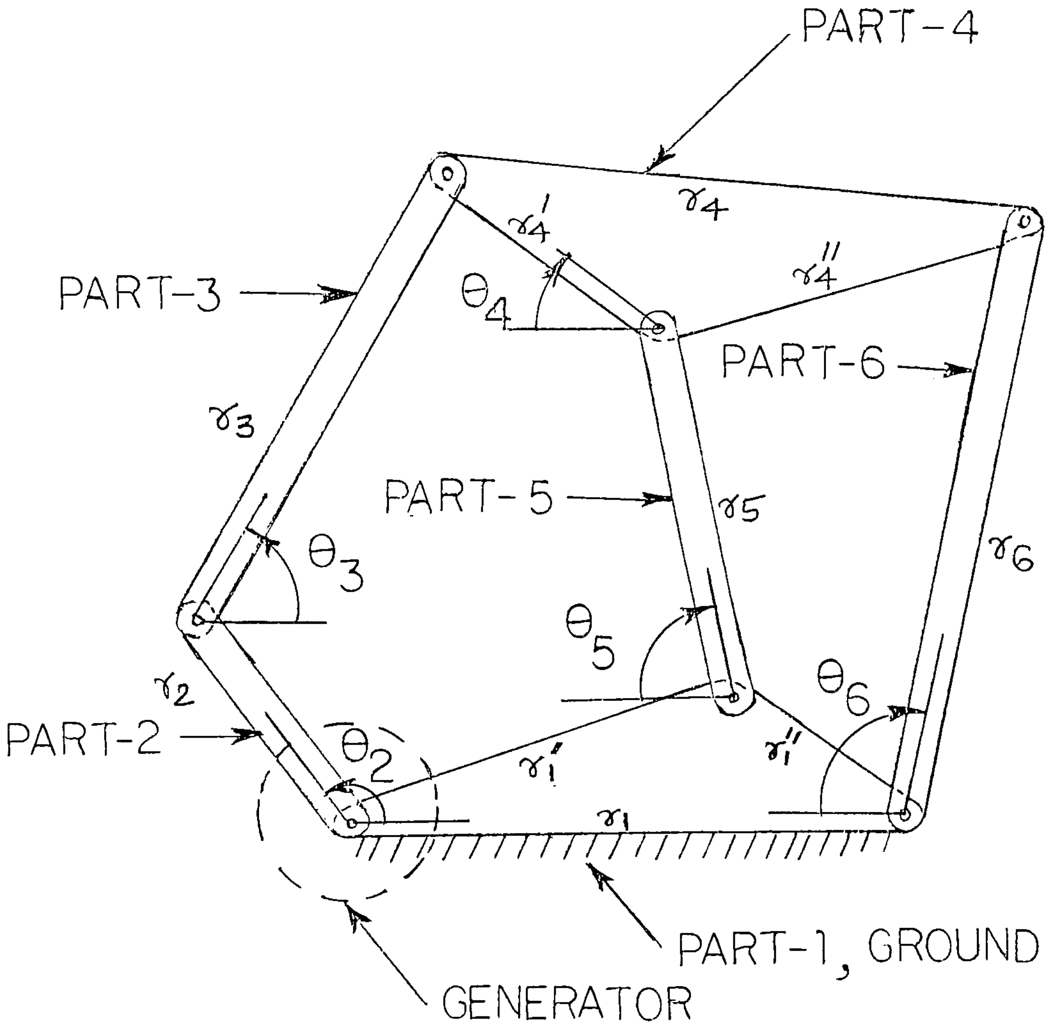


FIG. 7.16 - POSITION

STEPHENSON'S KINEMATIC CHAIN

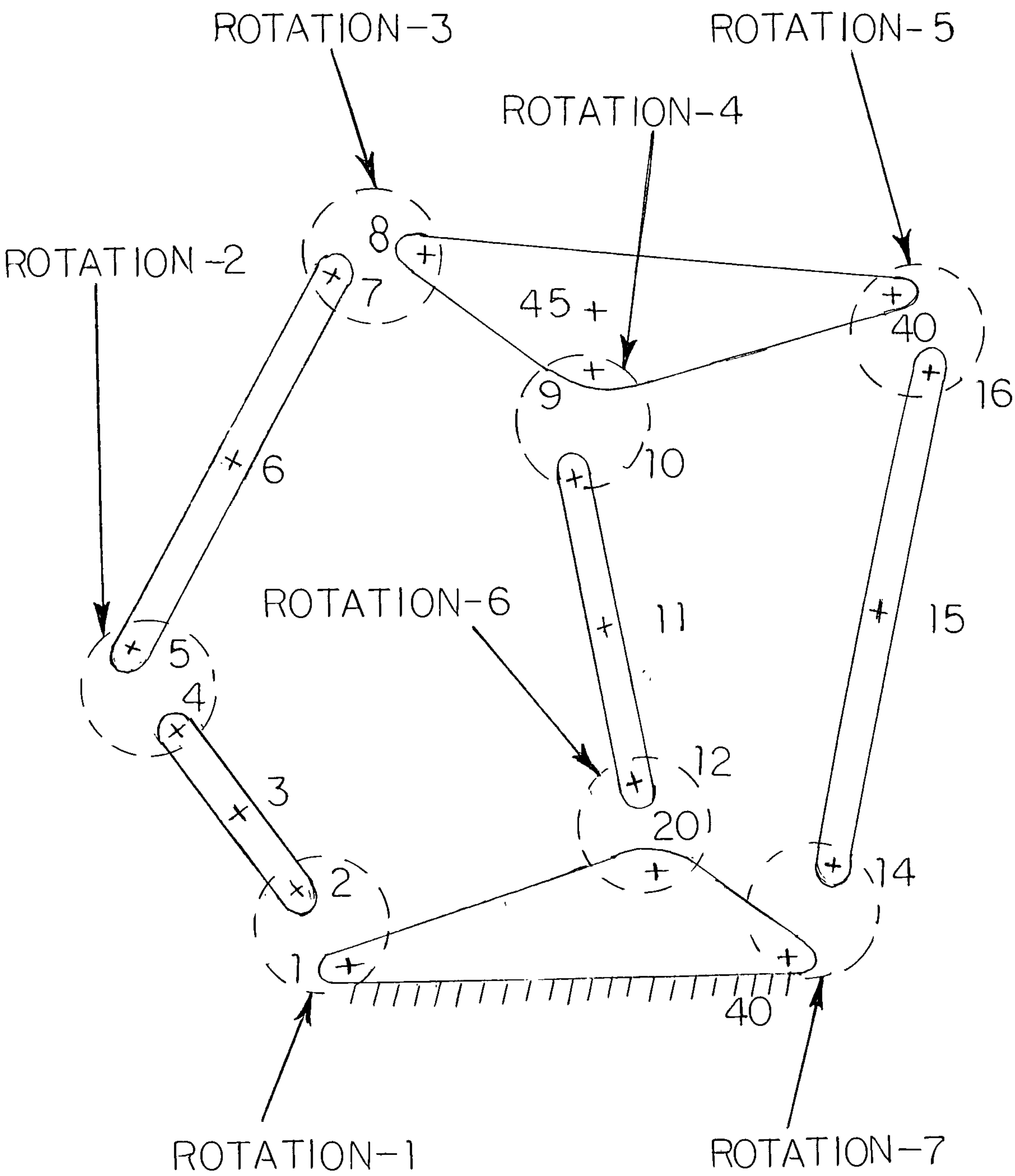
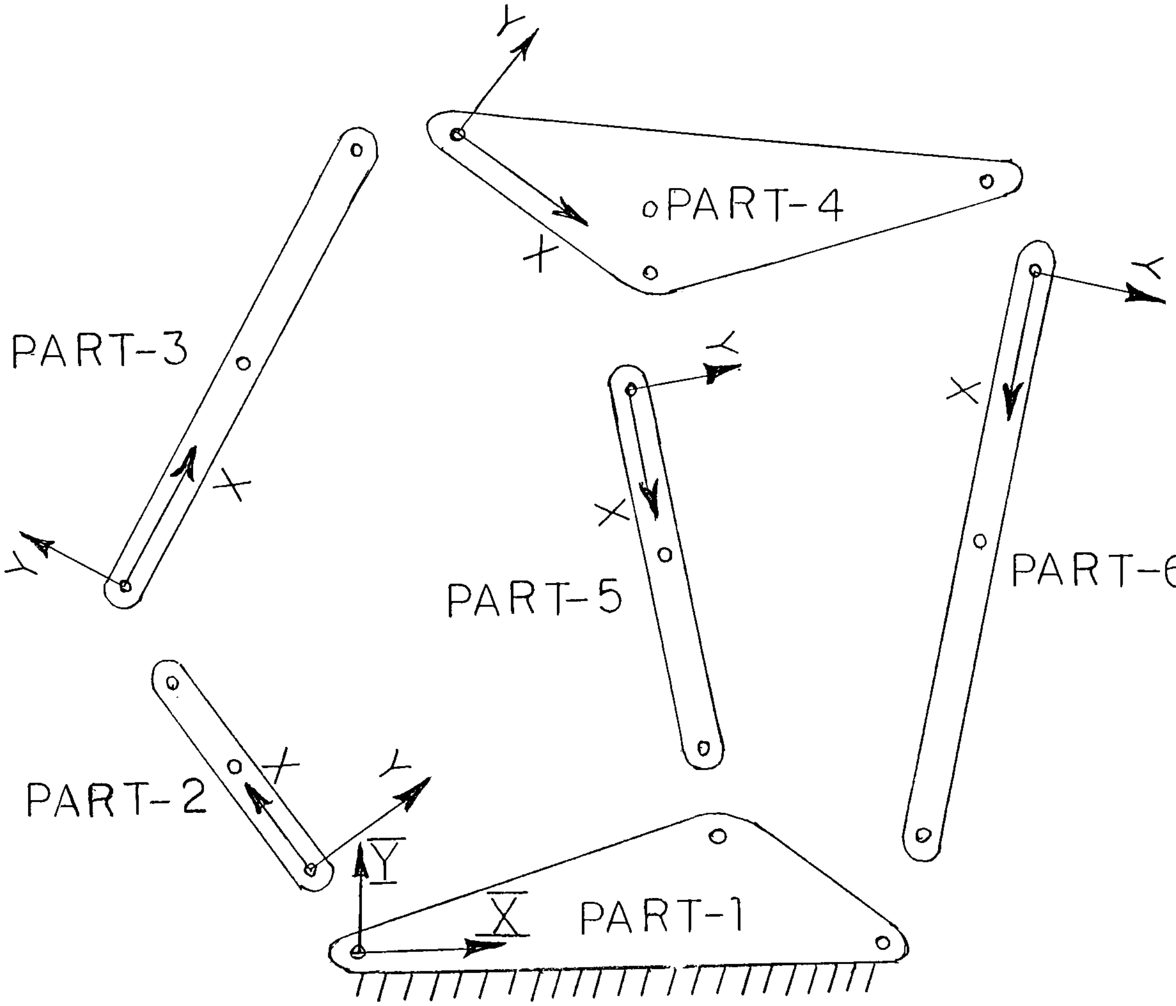


FIG. 7.17 - MARKERS

STEPHENSON'S KINEMATIC CHAIN



$\overline{XY}$- GROUND REFERENCE AXIS

XY- LOCAL PART REFERENCE AXIS

FIG. 7.18- AXES

```
STEPHENSON'S KINEMATIC CHAIN
LIST

PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/30,POINT,PART=1,X=4.8,Y=0
MARKER/20,GMARKER,PART=1,X=3.4,Y=0.90861048,ANGLE=15.5

PART/2,MASS=0.10,CM=3,INERTIA=0.02133,ANGLE=150
PART/2,DEGDANGLE=24998.149
MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/3,GMARKER,PART=2,X=0.8,Y=0,ANGLE=0,Y=0
MARKER/4,POINT,PART=2,X=1.6,Y=0

PART/3,MASS=0.60,CM=6,INERTIA=0.968,ANGLE=60
MARKER/5,POINT,PART=3,X=0,Y=0
MARKER/6,GMARKER,PART=3,X=2.25,Y=0,ANGLE=0
MARKER/7,POINT,PART=3,X=4.5,Y=0

PART/4,MASS=0.30,CM=45,INERTIA=0.21796614,ANGLE=-49
MARKER/8,POINT,PART=4,X=0,Y=0
MARKER/9,GMARKER,PART=4,X=2.1,Y=0,ANGLE=0
MARKER/40,GMARKER,PART=4,X=3.4971568,Y=2.8319418,ANGLE=39
MARKER/45,GMARKER,PART=4,X=1.8,Y=0,ANGLE=27

PART/5,MASS=0.35,CM=11,INERTIA=0.14765,ANGLE=-65
MARKER/10,POINT,PART=5,X=0,Y=0
MARKER/11,GMARKER,PART=5,X=1.2,Y=0,ANGLE=0
MARKER/12,POINT,PART=5,X=2.4,Y=0

PART/6,MASS=0.50,CM=15,INERTIA=0.66666,ANGLE=-97
MARKER/16,POINT,PART=6,X=0,Y=0
MARKER/15,GMARKER,PART=6,X=2,Y=0,ANGLE=0
MARKER/14,POINT,PART=6,X=4,Y=0

ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=7,J=8
ROTATION/4,I=9,J=10
ROTATION/5,I=40,J=16
ROTATION/6,I=12,J=20
ROTATION/7,I=14,J=30


GENERATOR/1,ROTATIONAL,ON=2,CONSTVEL,DEGPAR=24998.149,PAR=150.0D

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.02,STEPS=50,NOPLOT,RANGLE


REQUEST/1,DISPLACEMENT,I=15,J=1

REQUEST/2,VELOCITY,I=6,J=1
REQUEST/3,VELOCITY,I=45,J=1
REQUEST/4,VELOCITY,I=11,J=1
REQUEST/5,VELOCITY,I=15,J=1

REQUEST/6,ACCELERATION,I=6,J=1
REQUEST/7,ACCELERATION,I=45,J=1
```

```
REQUEST/8,ACCELERATION,I=11,J=1
REQUEST/9,ACCELERATION,I=15,J=1
```

*** NOTE ***

SOME OF THE OUTPUTS ARE NOT ENCLOSED DUE TO THE LIMITED AMOUNT OF SPACE AVAILABILITY.

```
END
```

OUTPUTS

Output comments are the same as example 7.2 .

```
-- DEFAULT VALUE (TSM1) -- SYSTEM/TS= 4.0000E-04

SYSTEM HAS    0 DEGREE(S) OF FREEDOM
SYSTEM WILL BE SIMULATED IN KINEMATIC MODE


*---- INPUT DATA LOOP CLOSURE CHECK  ----*
I---------------------------------------I
I ROTATION I DISPLACEMENT I   VELOCITY  I
I          I    ERROR     I    ERROR    I
I----------I--------------I-------------I
I        5 I  1.73298D-01 I 0.00000D+00 I
I        3 I  1.46428D-01 I 6.98080D+02 I
I----------I--------------I-------------I


LOOP CLOSURE DISPLACEMENT SOLUTION

CONVERGENCE WITHIN   2.96156D-14 IN  4 ITERATIONS

LOOP CLOSURE VELOCITY SOLUTION


CORRECTED INITIAL CONDITIONS


PART/     1     0.000000000000000D+00 DEG    0.000000000000000D+00 RAD/SEC
PART/     2     1.500000000000000D+02 DEG    4.363000069541280D+02 RAD/SEC
PART/     3     5.846250540670610D+01 DEG    8.790284480507062D+01 RAD/SEC
PART/     4    -4.773065315817662D+01 DEG    1.107950491391986D+02 RAD/SEC
PART/     5    -6.486538032911962D+01 DEG    2.365684457144048D+02 RAD/SEC
PART/     6    -9.885838328310470D+01 DEG    1.544671080212150D+02 RAD/SEC

KFLAG= 0 ORDER= 0 IFCT=    51 H= 0.40000D-03 ITER=     4


IN THE OUTPUT PHASE  2356 WORDS OF MEMORY WERE REQUIRED
```

STEPHENSON'S KINEMATIC CHAIN

REQUEST NUMBER 3

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 45 RELATIVE TO MARKER 1	ANGLE (RADIANS)	MAGNITUDE OF THE ANGULAR VELOCITY (RAD) OF MARKER 45 RELATIVE TO MARKER 1
0.0000E+00	5.99607E+02	3.59661E+00	1.10795E+02
4.0000E-04	5.72286E+02	3.68695E+00	1.09693E+02
8.0000E-04	5.40372E+02	3.77238E+00	1.07199E+02
1.2000E-03	5.04676E+02	3.85233E+00	1.03361E+02
1.6000E-03	4.65921E+02	3.92633E+00	9.82512E+01
2.0000E-03	4.24747E+02	3.99405E+00	9.19671E+01
2.4000E-03	3.81681E+02	4.05520E+00	8.46161E+01
2.8000E-03	3.37095E+02	4.10960E+00	7.62997E+01
3.2000E-03	2.91150E+02	4.15706E+00	6.70925E+01
3.6000E-03	2.43732E+02	4.19741E+00	5.70204E+01
4.0000E-03	1.94390E+02	4.23043E+00	4.60383E+01
4.4000E-03	1.42259E+02	4.25581E+00	3.40086E+01
4.8000E-03	8.59501E+01	4.27303E+00	2.06777E+01
5.2000E-03	2.34096E+01	4.28135E+00	5.64901E+00
5.6000E-03	4.82977E+01	1.13802E+00	-1.16474E+01
6.0000E-03	1.33278E+02	1.12457E+00	-3.19830E+01
6.4000E-03	2.37148E+02	1.09698E+00	-5.63340E+01
6.8000E-03	3.67269E+02	1.05185E+00	-8.57944E+01
7.2000E-03	5.32324E+02	9.84468E-01	-1.21243E+02
7.6000E-03	7.39826E+02	8.88776E-01	-1.62455E+02
8.0000E-03	9.88586E+02	7.57885E-01	-2.06278E+02
8.4000E-03	1.25268E+03	5.86398E-01	-2.44115E+02
8.8000E-03	1.46047E+03	3.75789E-01	-2.61288E+02
9.2000E-03	1.49372E+03	1.42467E-01	-2.42879E+02
9.6000E-03	1.25016E+03	6.20551E+00	-1.85755E+02
1.0000E-02	7.69326E+02	6.04275E+00	-1.06950E+02
1.0400E-02	2.56410E+02	5.96165E+00	-3.44793E+01
1.0800E-02	1.24952E+02	2.81164E+00	1.67441E+01
1.1200E-02	3.61370E+02	2.85230E+00	4.92412E+01
1.1600E-02	4.98823E+02	2.92213E+00	6.99432E+01
1.2000E-02	5.76799E+02	3.00842E+00	8.37812E+01
1.2400E-02	6.19021E+02	3.10361E+00	9.34824E+01
1.2800E-02	6.38661E+02	3.20308E+00	1.00457E+02
1.3200E-02	6.43063E+02	3.30386E+00	1.05414E+02
1.3600E-02	6.36463E+02	3.40393E+00	1.08701E+02
1.4000E-02	6.21440E+02	3.50180E+00	1.10474E+02
1.4400E-02	5.99673E+02	3.59636E+00	1.10796E+02
1.4800E-02	5.72365E+02	3.68672E+00	1.09698E+02
1.5200E-02	5.40462E+02	3.77216E+00	1.07207E+02
1.5600E-02	5.04776E+02	3.85212E+00	1.03372E+02
1.6000E-02	4.66028E+02	3.92614E+00	9.82664E+01
1.6400E-02	4.24859E+02	3.99387E+00	9.19853E+01
1.6800E-02	3.81798E+02	4.05505E+00	8.46370E+01
1.7200E-02	3.37216E+02	4.10946E+00	7.63230E+01
1.7600E-02	2.91274E+02	4.15694E+00	6.71182E+01
1.8000E-02	2.43861E+02	4.19731E+00	5.70484E+01
1.8400E-02	1.94525E+02	4.23036E+00	4.60689E+01
1.8800E-02	1.42403E+02	4.25575E+00	3.40423E+01
1.9200E-02	8.61074E+01	4.27300E+00	2.07153E+01
1.9600E-02	2.35869E+01	4.28134E+00	5.69179E+00
2.0000E-02	4.80911E+01	1.13804E+00	-1.15977E+01

REQUEST NUMBER 9

TIME	MAGNITUDE OF THE LINEAR ACCELERATION OF MARKER 15 RELATIVE TO MARKER 1	ANGLE (RADIANS)	MAGNITUDE OF THE ANGULAR ACCELERATION (RADS) OF MARKER 15 RELATIVE TO MARKER 1
0.0000E+00	6.67084E+04	5.33144E+00	-2.33066E+04
4.0000E-04	6.60890E+04	5.50262E+00	-2.55732E+04
8.0000E-04	6.50153E+04	5.65793E+00	-2.70790E+04
1.2000E-03	6.36427E+04	5.79950E+00	-2.79843E+04
1.6000E-03	6.20978E+04	5.92844E+00	-2.84234E+04
2.0000E-03	6.05031E+04	6.04546E+00	-2.85238E+04
2.4000E-03	5.90000E+04	6.15114E+00	-2.84170E+04
2.8000E-03	5.77653E+04	6.24591E+00	-2.82459E+04
3.2000E-03	5.70225E+04	4.67106E-02	-2.81686E+04
3.6000E-03	5.70528E+04	1.19605E-01	-2.83645E+04
4.0000E-03	5.82106E+04	1.80503E-01	-2.90430E+04
4.4000E-03	6.09540E+04	2.27946E-01	-3.04603E+04
4.8000E-03	6.58980E+04	2.60158E-01	-3.29470E+04
5.2000E-03	7.39024E+04	2.75436E-01	-3.69512E+04
5.6000E-03	8.62046E+04	2.72473E-01	-4.31022E+04
6.0000E-03	1.04603E+05	2.50330E-01	-5.22940E+04
6.4000E-03	1.31658E+05	2.07899E-01	-6.57684E+04
6.8000E-03	1.70759E+05	1.42875E-01	-8.50998E+04
7.2000E-03	2.25509E+05	5.02925E-02	-1.11762E+05
7.6000E-03	2.96968E+05	6.20359E+00	-1.45404E+05
8.0000E-03	3.75897E+05	6.01793E+00	-1.79119E+05
8.4000E-03	4.29098E+05	5.73821E+00	-1.90589E+05
8.8000E-03	4.00068E+05	5.25582E+00	-1.36533E+05
9.2000E-03	3.37201E+05	4.20927E+00	2.26846E+04
9.6000E-03	5.54642E+05	3.08893E+00	2.47094E+05
1.0000E-02	7.67217E+05	2.63083E+00	3.80341E+05
1.0400E-02	6.73917E+05	2.45788E+00	3.36911E+05
1.0800E-02	4.44181E+05	2.44097E+00	2.22086E+05
1.1200E-02	2.58694E+05	2.55106E+00	1.28864E+05
1.1600E-02	1.46805E+05	2.80398E+00	7.03681E+04
1.2000E-02	8.93112E+04	3.23424E+00	3.53756E+04
1.2400E-02	6.70383E+04	3.78836E+00	1.39270E+04
1.2800E-02	6.28278E+04	4.28201E+00	1.69375E+02
1.3200E-02	6.41075E+04	4.64475E+00	-9.06484E+03
1.3600E-02	6.57921E+04	4.91748E+00	-1.54881E+04
1.4000E-02	6.66749E+04	5.13933E+00	-2.00503E+04
1.4400E-02	6.67092E+04	5.33096E+00	-2.32994E+04
1.4800E-02	6.60913E+04	5.50218E+00	-2.55682E+04
1.5200E-02	6.50186E+04	5.65753E+00	-2.70758E+04
1.5600E-02	6.36467E+04	5.79914E+00	-2.79826E+04
1.6000E-02	6.21021E+04	5.92811E+00	-2.84228E+04
1.6400E-02	6.05073E+04	6.04517E+00	-2.85238E+04
1.6800E-02	5.90037E+04	6.15088E+00	-2.84175E+04
1.7200E-02	5.77680E+04	6.24567E+00	-2.82463E+04
1.7600E-02	5.70236E+04	4.65012E-02	-2.81686E+04
1.8000E-02	5.70514E+04	1.19426E-01	-2.83634E+04
1.8400E-02	5.82056E+04	1.80357E-01	-2.90403E+04
1.8800E-02	6.09441E+04	2.27839E-01	-3.04553E+04
1.9200E-02	6.58813E+04	2.60094E-01	-3.29386E+04
1.9600E-02	7.38760E+04	2.75419E-01	-3.69380E+04
2.0000E-02	8.61647E+04	2.72506E-01	-4.30822E+04

7.7 EXAMPLE:

A undamped two degree freedom spring mass system having weights of W1 = W2 =50 lbs, spring constants k1 =20 lb/in and k2 =15 lb/in, and unstretched lengths L1 = L2 =3 inches is allowed to vibrate freely. The initial conditions are X1(0) =0, X2(0) =0, D(X1(0)) = 25 inch/sec, D(X2(0)) = 25 inch/sec, where D is the first derivative of displacement X. Calculate the displacement, velocity, and acceleration of each mass due to the free vibration.

UNDAMPED FREE VIBRATION

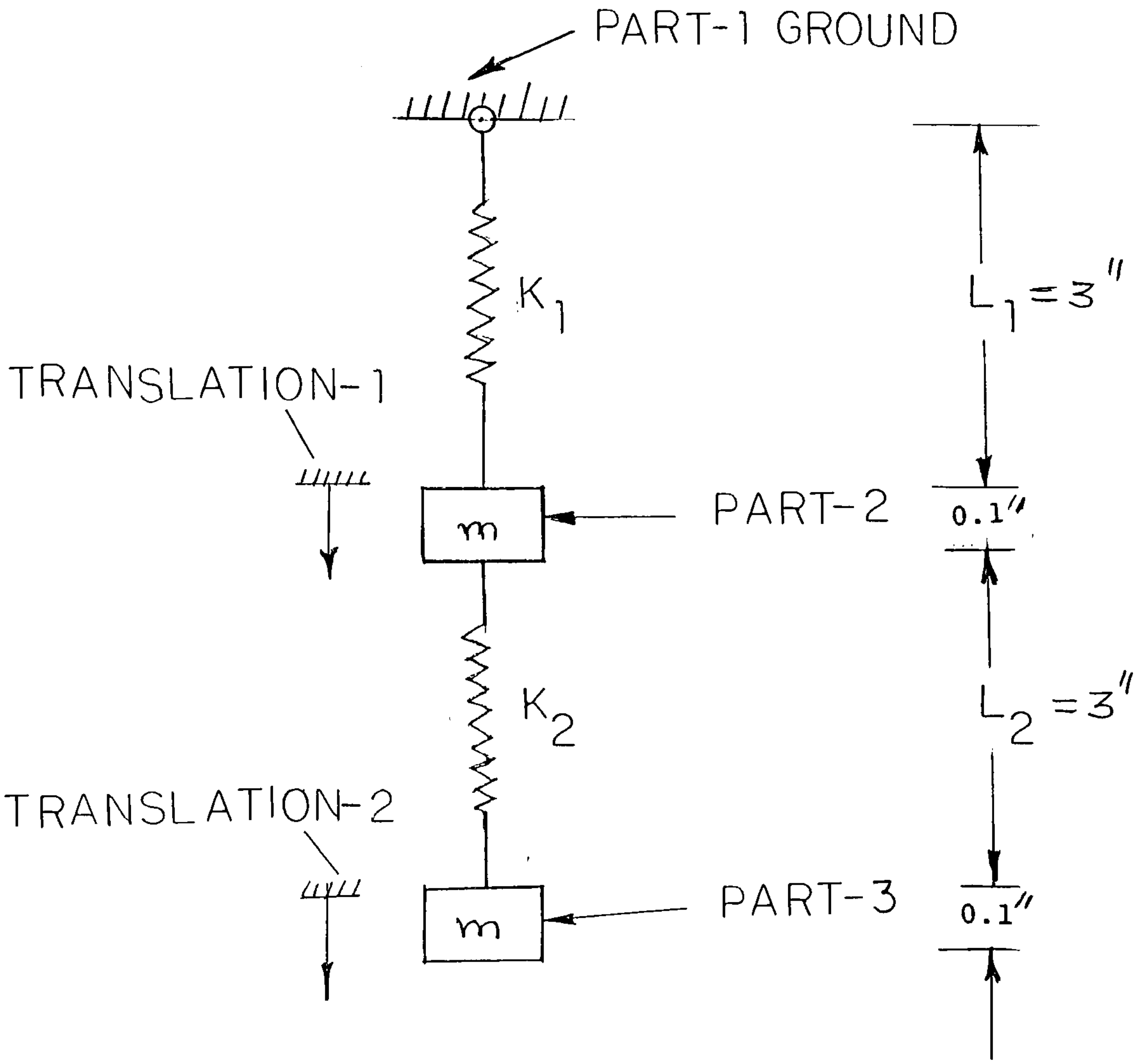


FIG. 7.19 - POSITION

UNDAMPED FREE VIBRATION

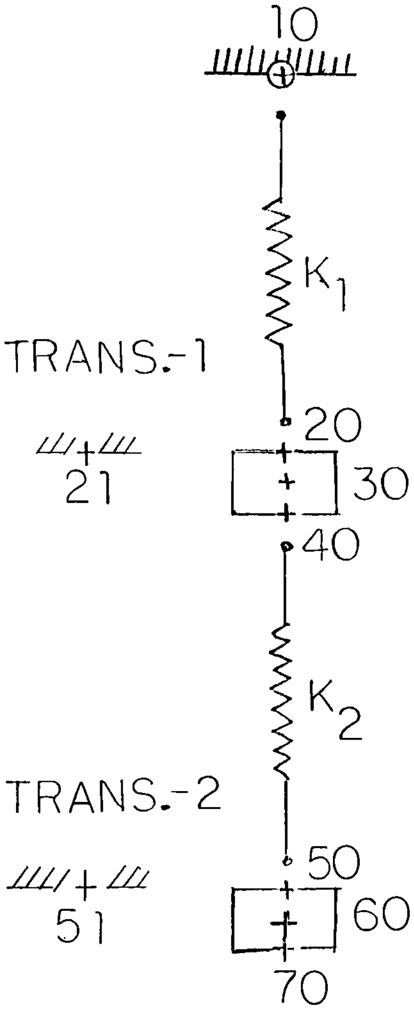


FIG.7.20 - MARKERS

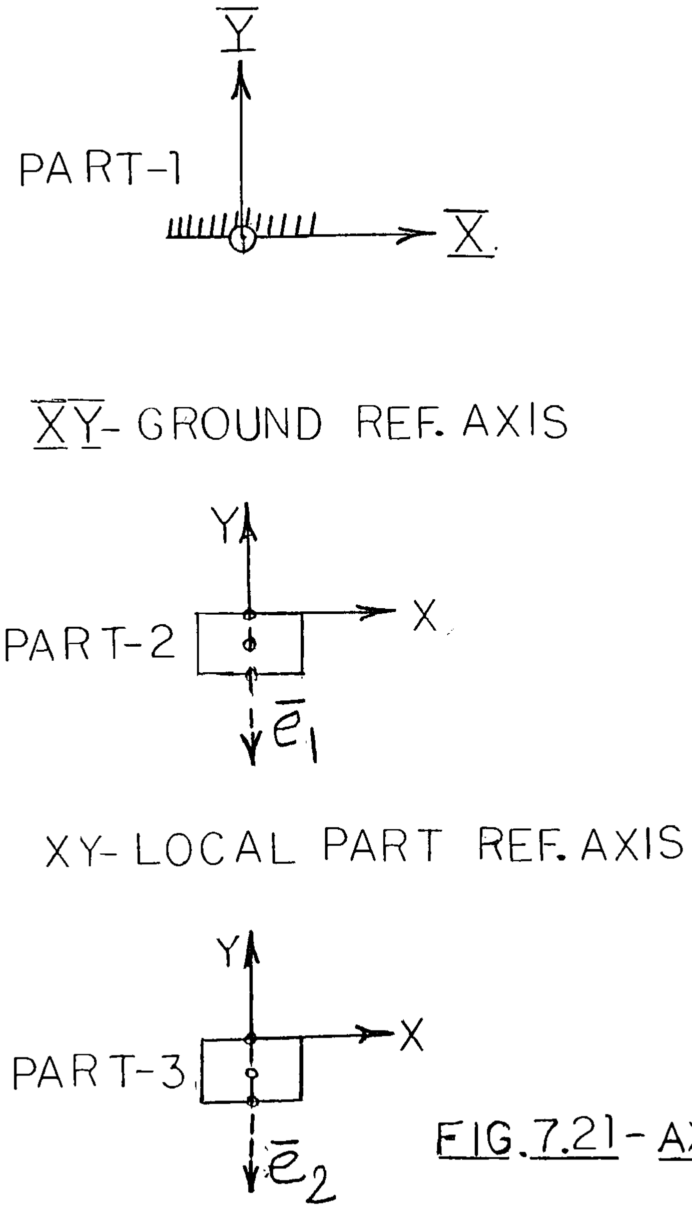


FIG.7.21 - AXES

$\bar{e}_1, \bar{e}_2$ - UNIT VECTORS. ASSOCIATED WITH MARERS 20, AND 50 RESPECTIVELY.

```
UNDAMPED FREE VIBRATION [ TWO DEGREE OF FREEDOM ]
LIST

PART/1,GROUND
MARKER/10,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/21,GMARKER,PART=1,X=0,Y=-3.0,ANGLE=-90
      FOR TRANSLATIONAL MOTION MARKER 21 MUST BE A GMARKER.
      ANGLE==> -90 DESCRIBES THE POSITION OF UNIT VECTOR E2.
MARKER/51,GMARKER,PART=1,X=0,Y=-6.1,ANGLE=-90
      FOR TRANSLATIONAL MOTION MARKER 51 MUST BE A GMARKER.
      ANGLE==> -90 DESCRIBES THE POSITION OF UNIT VECTOR E3.

PART/2,MASS=50,CM=30,INERTIA=0.0,ANGLE=0
      NOTE: DRAM WILL DIVIDE 50 LBM BY THE GRAVITATIONAL CONSTANT.
MARKER/20,GMARKER,PART=2,X=0,Y=0,ANGLE=-90
      FOR TRANSLATIONAL MOTION MARKER 20 MUST BE A GMARKER.
      ANGLE==> -90 DESCRIBES THE POSITION OF UNIT VECTOR E2.
MARKER/30,POINT,PART=2,X=0.,Y=-0.05
MARKER/40,POINT,PART=2,X=0,Y=-0.1

PART/3,MASS=50,CM=60,INERTIA=0.0,ANGLE=0
MARKER/50,GMARKER,PART=3,X=0,Y=0,ANGLE=-90
      FOR TRANSLATIONAL MOTION, MARKER 50 MUST BE A GMARKER.
      ANGLE==> -90 DESCRIBES THE POSITION OF UNIT VECTOR E3.
MARKER/60,POINT,PART=3,X=0,Y=-0.05
MARKER/70,POINT,PART=3,X=0,Y=-0.1

TRANSLATION/1,I=20,J=21,TRANS=0,DTRANS=25
      INITIAL CONDITIONS FOR BODY # 1: TRANS==> DISPLACEMENT X(0)=0
      DTRANS==> VELOCITY V(0)= 25 INCH/SEC.
TRANSLATION/2,I=50,J=51,TRANS=0,DTRANS=25
      INITIAL CONDITIONS FOR BODY # 2: TRANS==> DISPLACEMENT X(0)=0
      DTRANS==> VELOCITY V(0)= 25 INCH/SEC.

FIELD/1,TRANSLATIONAL,SPRING,I=10,J=20,PAR=20,3
      THE SPRING IS ATTACHED BETWEEN MARKERS I=10 & J=20
      PAR==> THE FIRST VALUE (20 LB/INCH) IS A SPRING CONSTANT. THE
      SECOND VALUE (3 INCHES) IS A UNSTRETCHED SPRING LENGTH IN INCHES.
      THIS PARAMETER VALUE SEQUENCE CAN NOT BE CHANGED.
FIELD/2,TRANSLATIONAL,SPRING,I=40,J=50,PAR=15,3
      THE SPRING IS ATTACHED BETWEEN MARKERS I=40 & J=50.
      PAR==> THE FIRST VALUE (15 LB/INCH) IS A SPRING CONSTANT. THE
      SECOND VALUE (3 INCHES) IS A UNSTRETCHED SPRING LENGTH IN INCHES.
      THIS PARAMETER VALUE SEQUENCE CAN NOT BE CHANGED.

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.015,STEPS=50,NOPLOT

REQUEST/1,DISPLACEMENT,I=20,J=10
REQUEST/2,DISPLACEMENT,I=50,J=10

REQUEST/3,VELOCITY,I=20,J=10
REQUEST/4,VELOCITY,I=50,J=10

REQUEST/5,ACCELERATION,I=20,J=10
REQUEST/6,ACCELERATION,I=50,J=10

      *** NOTE ***
```

WHENEVER THERE ARE NO COMMENTS AFTER STATEMENTS IN THE PROGRAM, THEN ASSUME THAT THOSE STATEMENTS ARE EXACTLY SIMILAR TO THOSE OF THE FIRST TWO EXAMPLES OF THIS USER'S MANUAL.

SOME OF THE OUTPUTS ARE NOT ENCLOSED DUE THE LIMITED AMOUNT OF SPACE AVAILABILITY.

END

OUTPUTS

Output comments are the same as examples 7.1 and 7.2 .

UNDAMPED FREE VIBRATION [TWO DEGREE OF FREEDOM]

REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR DISPLACEMENT OF MARKER 20 RELATIVE TO MARKER 10	ANGLE (DEGREES)	MAGNITUDE OF THE ANGULAR DISPLACEMENT (DEGS) OF MARKER 20 RELATIVE TO MARKER 10
0.0000E+00	3.00000E+00	2.70000E+02	-9.00000E+01
3.0000E-04	3.00753E+00	2.70000E+02	-9.00000E+01
6.0000E-04	3.01508E+00	2.70000E+02	-9.00000E+01
9.0000E-04	3.02267E+00	2.70000E+02	-9.00000E+01
1.2000E-03	3.03029E+00	2.70000E+02	-9.00000E+01
1.5000E-03	3.03795E+00	2.70000E+02	-9.00000E+01
1.8000E-03	3.04564E+00	2.70000E+02	-9.00000E+01
2.1000E-03	3.05336E+00	2.70000E+02	-9.00000E+01
2.4000E-03	3.06112E+00	2.70000E+02	-9.00000E+01
2.7000E-03	3.06891E+00	2.70000E+02	-9.00000E+01
3.0000E-03	3.07674E+00	2.70000E+02	-9.00000E+01
3.3000E-03	3.08459E+00	2.70000E+02	-9.00000E+01
3.6000E-03	3.09249E+00	2.70000E+02	-9.00000E+01
3.9000E-03	3.10041E+00	2.70000E+02	-9.00000E+01
4.2000E-03	3.10837E+00	2.70000E+02	-9.00000E+01
4.5000E-03	3.11637E+00	2.70000E+02	-9.00000E+01
4.8000E-03	3.12439E+00	2.70000E+02	-9.00000E+01
5.1000E-03	3.13245E+00	2.70000E+02	-9.00000E+01
5.4000E-03	3.14054E+00	2.70000E+02	-9.00000E+01
5.7000E-03	3.14867E+00	2.70000E+02	-9.00000E+01
6.0000E-03	3.15682E+00	2.70000E+02	-9.00000E+01
6.3000E-03	3.16501E+00	2.70000E+02	-9.00000E+01
6.6000E-03	3.17324E+00	2.70000E+02	-9.00000E+01
6.9000E-03	3.18149E+00	2.70000E+02	-9.00000E+01
7.2000E-03	3.18978E+00	2.70000E+02	-9.00000E+01
7.5000E-03	3.19810E+00	2.70000E+02	-9.00000E+01
7.8000E-03	3.20645E+00	2.70000E+02	-9.00000E+01
8.1000E-03	3.21483E+00	2.70000E+02	-9.00000E+01
8.4000E-03	3.22324E+00	2.70000E+02	-9.00000E+01
8.7000E-03	3.23169E+00	2.70000E+02	-9.00000E+01
9.0000E-03	3.24017E+00	2.70000E+02	-9.00000E+01
9.3000E-03	3.24868E+00	2.70000E+02	-9.00000E+01
9.6000E-03	3.25722E+00	2.70000E+02	-9.00000E+01
9.9000E-03	3.26579E+00	2.70000E+02	-9.00000E+01
1.0200E-02	3.27439E+00	2.70000E+02	-9.00000E+01
1.0500E-02	3.28303E+00	2.70000E+02	-9.00000E+01
1.0800E-02	3.29169E+00	2.70000E+02	-9.00000E+01
1.1100E-02	3.30039E+00	2.70000E+02	-9.00000E+01
1.1400E-02	3.30911E+00	2.70000E+02	-9.00000E+01
1.1700E-02	3.31787E+00	2.70000E+02	-9.00000E+01
1.2000E-02	3.32665E+00	2.70000E+02	-9.00000E+01
1.2300E-02	3.33547E+00	2.70000E+02	-9.00000E+01
1.2600E-02	3.34432E+00	2.70000E+02	-9.00000E+01
1.2900E-02	3.35319E+00	2.70000E+02	-9.00000E+01
1.3200E-02	3.36210E+00	2.70000E+02	-9.00000E+01
1.3500E-02	3.37104E+00	2.70000E+02	-9.00000E+01
1.3800E-02	3.38000E+00	2.70000E+02	-9.00000E+01
1.4100E-02	3.38900E+00	2.70000E+02	-9.00000E+01
1.4400E-02	3.39802E+00	2.70000E+02	-9.00000E+01
1.4700E-02	3.40708E+00	2.70000E+02	-9.00000E+01
1.5000E-02	3.41616E+00	2.70000E+02	-9.00000E+01

7.8 EXAMPLE:

A damped spring mass system having a weight of W =40 lbs, a spring constant k =50 lb/inch, a length L =2.5 inches and a damping coefficient c =0.85 lb-s/inch is subjected to a force F =10 sin15t lb. The initial conditions are X(0) =0, D(X(0)) =4 inch/sec. Calculate the displacement, velocity, and amplitude of the forced vibration. For the amplitude of vibration use PAR(1) {Damping coefficient} =0.85, PAR(2) {Frequency of excitation force}=15, PAR(3) {Spring constant}=50, PAR(4) {Mass of the system}=40/386.088, PAR(5) {force (Fo)}=10 WHERE GC=386.088.

FORCED VIBRATION
WITH
DAMPING

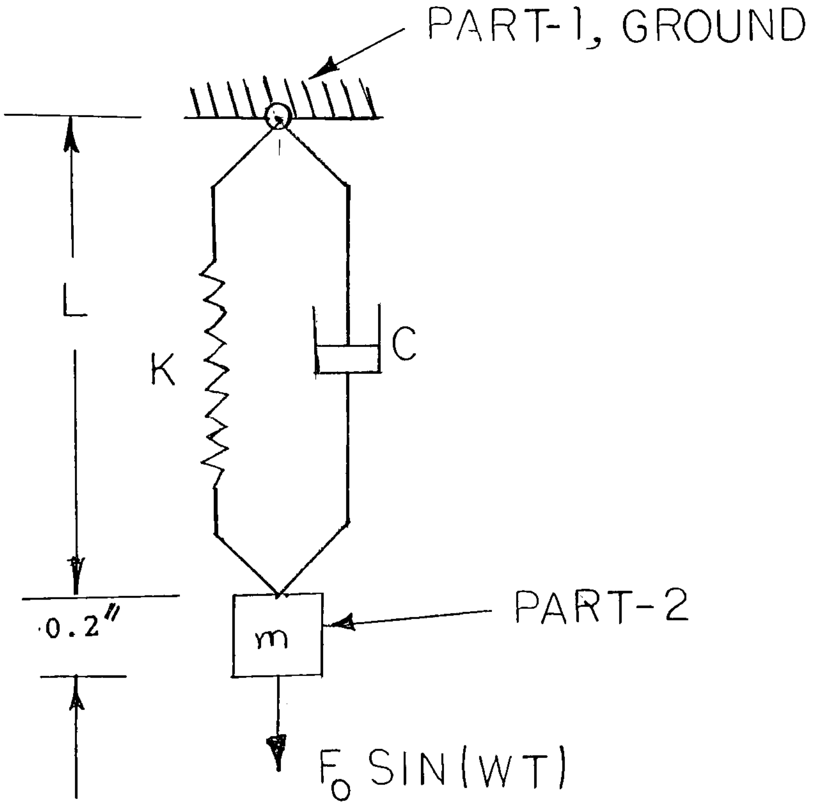
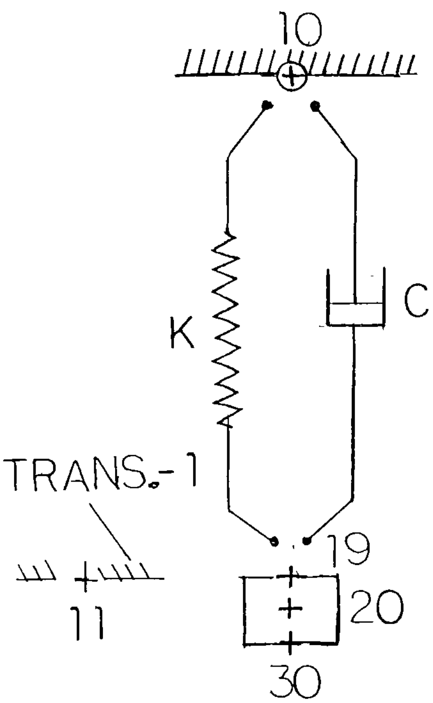
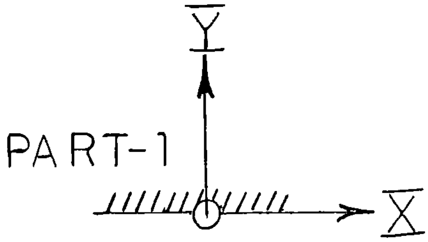


FIG. 7.22 - POSITION

FORCED VIBRATION WITH DAMPING





$\bar{X}\bar{Y}$ - GROUND REF. AXIS

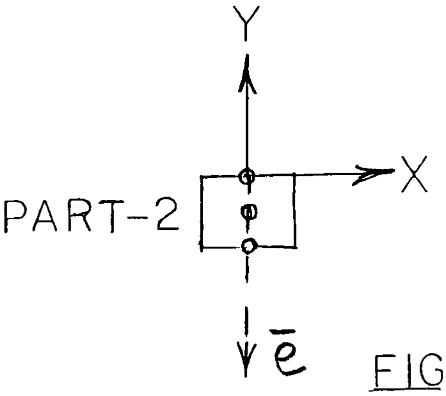


FIG. 7.24 - AXES

FIG. 7.23 - MARKERS

XY - LOCAL PART REF. AXIS

$\bar{e}$ - UNIT VECTOR ASSOCIATED WITH MARKER 19.

```
FORCED VIBRATION WITH UNDER DAMPING [SINGLE DEGREE OF FREEDOM]
LIST

PART/1,GROUND
MARKER/10,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/11,GMARKER,PART=1,X=0,Y=-2.5,ANGLE=-90

PART/2,MASS=40,CM=20,INERTIA=0.0,ANGLE=0
MARKER/19,GMARKER,PART=2,X=0,Y=0,ANGLE=-90
MARKER/20,POINT,PART=2,X=0,Y=-0.1
MARKER/30,POINT,PART=2,X=0,Y=-0.2

TRANSLATION/1,I=19,J=11,TRANSLATION=0,DTRANS=4,EXACT
      EXACT==> THE INITIAL VALUES OF THE ANGLE AND ANGULAR VELOCITY
      WILL BE HELD CONSTANT BY DRAM. IF THE ITERATION ON THE
      PROBLEM COORDINATES IS REQUIRED TO DETERMINE CONSISTENT
      INITIAL CONDITIONS, OTHER COORDINATES (LENGTH) WILL BE VARIED.

FIELD/1,TRANSLATIONAL,SPRING,I=10,J=19,PAR=50,2.5

FIELD/2,TRANSLATIONAL,DAMPER,I=10,J=19,PAR=0.85

FIELD/3,TRANSLATIONAL,INPUT,I=10,J=30,PAR=10,15
      INPUT==> LINKS THE "USUB" FUNCTION SUBPROGRAM TO DRAM.
      THE EXTERNAL FORCE F(t)=FO SIN (Wt) IS APPLIED TO
      MARKER 30.
      PAR==> THE MAGNITUDE OF FORCE (Fo)= 10 LBS,
      FREQUENCY OF EXCITATION FORCE (W)= 15 RAD/SEC.
      THE SEQUENCE OF THE PARAMETER VALUES COULD BE ANY, HOWEVER
      THE SAME SEQUENCE MUST BE USED IN THE FUNCTION SUBPROGRAM
      PARAMETERS.

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.015,STEPS=500,NOPLOT,RANGLE

REQUEST/1,DISPLACEMENT,I=19,J=10

REQUEST/2,VELOCITY,I=10,J=19

REQUEST/3,RSUB,I=19,J=10,TITLE=AMPLITUDE OF VIBRATION
,PAR=0.85,15,50,0.10360332,10
      RSUB==> A USER'S DEFINED REQUEST SUBROUTINE WHICH PROVIDES
      THE DESIRED RESULTS OF MARKERS 10 & 19.
      TITLE==> CAN BE A 48 CHARACTER OR LESS.
      PAR==> DAMPING COEFFICIENT (C)= 0.85 LB-SEC/INCH,
      FREQUENCY OF EXCITATION FORCE (W)= 15 RAD/SEC,
      SPRING CONSTANT (K)= 50 LB/INCH,
      MASS OF THE SYSTEM (M)= 40/386.088 =0.10360332 LB,
      MAGNITUDE OF EXCITATION FORCE (Fo)= 10 LBS.

      *** NOTE ***

      SOME OF THE OUTPUTS ARE NOT ENCLOSED DUE TO THE LIMITED
      AMOUNT OF SPACE AVAILABILITY.
END
```

```
* PROGRAM NAME  : SUBROUTINE USUB
*
* PROGRAMMER    : DEEPAK N. RODE
*
* DATE WRITTEN  : JUNE 17, 1986
*
* OBJECTIVE     : TO INPUT THE FORCING FUNCTION OF THE FORCED
*                 VIBRATION TO DRAM BY USING THE USUB FUNCTION
*                 SUBPROGRAM.
*
* DESCRIPTION OF PARAMETERS:
*
*            RAD=DISTANCE BETWEEN MARKERS I AND J  [ NOT NEEDED IN
*                THIS FUNCTION PROGRAM ].
*        APAR(1)=TIME (IN SIMULATION) ( PASSED BY DRAM ).
*            PAR=PARAMETERS. THE MAXIMUM PARAMETERS CAN BE 10.
*         NFIELD=IDENTIFICATION NO. OF THE FIELD. IT IS USEFUL
*                WHEN MORE THAN ONE FIELD STATEMENT IS USED IN THE
*                PROGRAM.
*             FO=FORCE.
*              W=FREQUENCY OF THE EXCITATION FORCE.
*           USUB=APPLIED FORCE FOR FORCE VIBRATION.
*
* Comment:
*
*       ARGUMENTS SUCH AS RAD,APAR..... OF THE FUNCTION USUB MUST BE
*       EXACTLY THE SAME AS STATED IN THE DRAM'S STANDARD FUNCTION
*       SUBPROGRAM FORM, THAT IS, " FUNCTION USUB(RAD,APAR,PAR,NFIELD)"
*       {STANDARD FORM}. THERE CAN NOT BE USER'S OWN ADDITIONAL
*       ARGUMENTS IN THE FUNCTION SUBPROGRAM STATEMENT. THE SUBPROGRAM
*       MUST BE WRITTEN IN DOUBLE PRECISION. FOR EX.--> REAL*8.
*
*       NFIELD==> ALLOWS ONE TO USE MORE THAN ONE FIELD STATEMENT
*       IN THE PROGRAM. FOR EXAMPLE
*       IF (NFIELD .EQ. 2) GO TO 100 (PERFORMS FIELD/2 ....
*       STATEMENT)
*       ELSE
*       FIELD/1...... STATEMENT.
*
*


      FUNCTION USUB(RAD,APAR,PAR,NFIELD)
      IMPLICIT REAL*8 (A-H,O-Z)

      DIMENSION PAR(2),APAR(1)

      TIME=APAR(1)
      FO=PAR(1)
      W=PAR(2)

      USUB=FO*SIN(W*TIME)


      RETURN

      END
```

```
* PROGRAM NAME   : SUBROUTINE RSUB
*
* PROGRAMMER     : DEEPAK N. RODE
*
* DATE WRITTEN   : JUNE 17, 1986
*
* OBJECTIVE      : TO FIND THE AMPLITUDE OF VIBRATION BY USING THE
*                  SUBROUTINE RSUB.
*
* DESCRIPTION OF PARAMETERS:
*
*              C= DAMPING COEFFICIENT.
*              W= FREQUENCY OF EXCITATION FORCE.
*             AK= SPRING CONSTANT.
*             AM= MASS OF THE SYSTEM.
*             FO= FORCE.
*             XP= AMPLITUDE OF VIBRATION.
*             ID= IDENTIFICATION NUMBER OF REQUEST.
*           TIME= SIMULATION TIME.
*            PAR= VALUES TO BE USED IN THE SUBROUTINE. THE MAXIMUM
*                 PARAMETERS CAN BE 10.
*      RESULT(1)= DRAM TAKES BACK THE CALCULATED VALUE THROUGH
*                 RESULT(1).
* Comments:
*
*       THIS SUBROUTINE RETURNS ONLY THREE RESULT VALUES TO DRAM.
*       DRAM RECEIVES THESE THREE RESULT VALUES THROUGH THE
*       "RESULT(3)" STATEMENT. SINCE THIS PARTICULAR EXAMPLE
*       THE SUBROUTINE CACULATES ONE RESULT VALUE DRAM WILL PRINT
*       THE RESULT VALUE IN THE SECOND COLUMN. THE ZEROS WILL BE
*       PRINTED IN THE NEXT TWO COLUMNS. SEE OUTPUT OF THIS EXAMPLE
*       (REQUEST/3).
*

      SUBROUTINE RSUB(ID,TIME,PAR,RESULT)
      IMPLICIT REAL*8 (A-H,O-Z)

      DIMENSION PAR(5),RESULT(1)

      C=PAR(1)
      W=PAR(2)
      AK=PAR(3)
      AM=PAR(4)
      FO=PAR(5)

      S=ATAN(C*W/(AK-AM*(W**2)))
      XP=(FO/((AK-AM*(W**2))**2+(C*W)**2)**0.5)*
     / SIN(W*TIME-S)

*     REFER TO THE ANALYTICAL SOLUTION OF EXAMPLE A.5 FOR THE ABOVE
*     MATHEMATICAL EQUATIONS.

      RESULT(1)=XP

      RETURN

      END
```

OUTPUTS

Request 3 : Since the RSUB subroutine is a special type of request routine, it allows only three results through the "RESULT (3)" statement. In this particular example, the amplitude of the vibartion needs to be calculated which is considered as RESULT(1) by DRAM. As DRAM is capable of handling three result values, it will print zeros in the remaining two columns in this particular example. DRAM prints the zeros in the third and fourth column because there is only one result request in the subroutine. Neglect the masses of links.

FORCED VIBRATION WITH UNDER DAMPING [SINGLE DEGREE OF FREEDOM]

REQUEST NUMBER 3

**** RSUB REQUEST ****

TIME	AMPLITUDE OF VIBRATION		
0.0000E+00	-1.45734E-01	0.00000E+00	0.00000E+00
3.0000E-05	-1.45597E-01	0.00000E+00	0.00000E+00
6.0000E-05	-1.45460E-01	0.00000E+00	0.00000E+00
9.0000E-05	-1.45322E-01	0.00000E+00	0.00000E+00
1.2000E-04	-1.45185E-01	0.00000E+00	0.00000E+00
1.5000E-04	-1.45047E-01	0.00000E+00	0.00000E+00
1.8000E-04	-1.44910E-01	0.00000E+00	0.00000E+00
2.1000E-04	-1.44773E-01	0.00000E+00	0.00000E+00
2.4000E-04	-1.44635E-01	0.00000E+00	0.00000E+00
2.7000E-04	-1.44498E-01	0.00000E+00	0.00000E+00
3.0000E-04	-1.44360E-01	0.00000E+00	0.00000E+00
3.3000E-04	-1.44222E-01	0.00000E+00	0.00000E+00
3.6000E-04	-1.44085E-01	0.00000E+00	0.00000E+00
3.9000E-04	-1.43947E-01	0.00000E+00	0.00000E+00
4.2000E-04	-1.43809E-01	0.00000E+00	0.00000E+00
4.5000E-04	-1.43672E-01	0.00000E+00	0.00000E+00
4.8000E-04	-1.43534E-01	0.00000E+00	0.00000E+00
5.1000E-04	-1.43396E-01	0.00000E+00	0.00000E+00
5.4000E-04	-1.43258E-01	0.00000E+00	0.00000E+00
5.7000E-04	-1.43121E-01	0.00000E+00	0.00000E+00
6.0000E-04	-1.42983E-01	0.00000E+00	0.00000E+00
6.3000E-04	-1.42845E-01	0.00000E+00	0.00000E+00
6.6000E-04	-1.42707E-01	0.00000E+00	0.00000E+00
6.9000E-04	-1.42569E-01	0.00000E+00	0.00000E+00
7.2000E-04	-1.42431E-01	0.00000E+00	0.00000E+00
7.5000E-04	-1.42293E-01	0.00000E+00	0.00000E+00
7.8000E-04	-1.42155E-01	0.00000E+00	0.00000E+00
8.1000E-04	-1.42017E-01	0.00000E+00	0.00000E+00
8.4000E-04	-1.41879E-01	0.00000E+00	0.00000E+00
8.7000E-04	-1.41741E-01	0.00000E+00	0.00000E+00
9.0000E-04	-1.41603E-01	0.00000E+00	0.00000E+00
9.3000E-04	-1.41465E-01	0.00000E+00	0.00000E+00
9.6000E-04	-1.41326E-01	0.00000E+00	0.00000E+00
9.9000E-04	-1.41188E-01	0.00000E+00	0.00000E+00
1.0200E-03	-1.41050E-01	0.00000E+00	0.00000E+00
1.0500E-03	-1.40912E-01	0.00000E+00	0.00000E+00
1.0800E-03	-1.40773E-01	0.00000E+00	0.00000E+00
1.1100E-03	-1.40635E-01	0.00000E+00	0.00000E+00
1.1400E-03	-1.40497E-01	0.00000E+00	0.00000E+00
1.1700E-03	-1.40358E-01	0.00000E+00	0.00000E+00
1.2000E-03	-1.40220E-01	0.00000E+00	0.00000E+00
1.2300E-03	-1.40081E-01	0.00000E+00	0.00000E+00
1.2600E-03	-1.39943E-01	0.00000E+00	0.00000E+00
1.2900E-03	-1.39804E-01	0.00000E+00	0.00000E+00
1.3200E-03	-1.39666E-01	0.00000E+00	0.00000E+00
1.3500E-03	-1.39527E-01	0.00000E+00	0.00000E+00
1.3800E-03	-1.39389E-01	0.00000E+00	0.00000E+00
1.4100E-03	-1.39250E-01	0.00000E+00	0.00000E+00
1.4400E-03	-1.39111E-01	0.00000E+00	0.00000E+00
1.4700E-03	-1.38973E-01	0.00000E+00	0.00000E+00
1.5000E-03	-1.38834E-01	0.00000E+00	0.00000E+00
1.5300E-03	-1.38695E-01	0.00000E+00	0.00000E+00

7.9 EXAMPLE:

A stone crushing toggle mechanism consists of six links. Link 2 is rotating at 3.14 rad/sec (180 degree/sec) (cw). Calculate the displacement velocity and acceleration of link 6. Consider lengths of links (parts) as: r2 =1 inch, r3 =5 inches, r4 =4 inches, r5 = 5 inches. Angles: Theta 2 =225 degrees ccw, Theta 3 =14 degrees ccw, Theta 4 =62 degrees ccw, Theta 5 =112 degrees ccw. Angles measured in the clockwise direction are negative.

TOGGLE MECHANISM

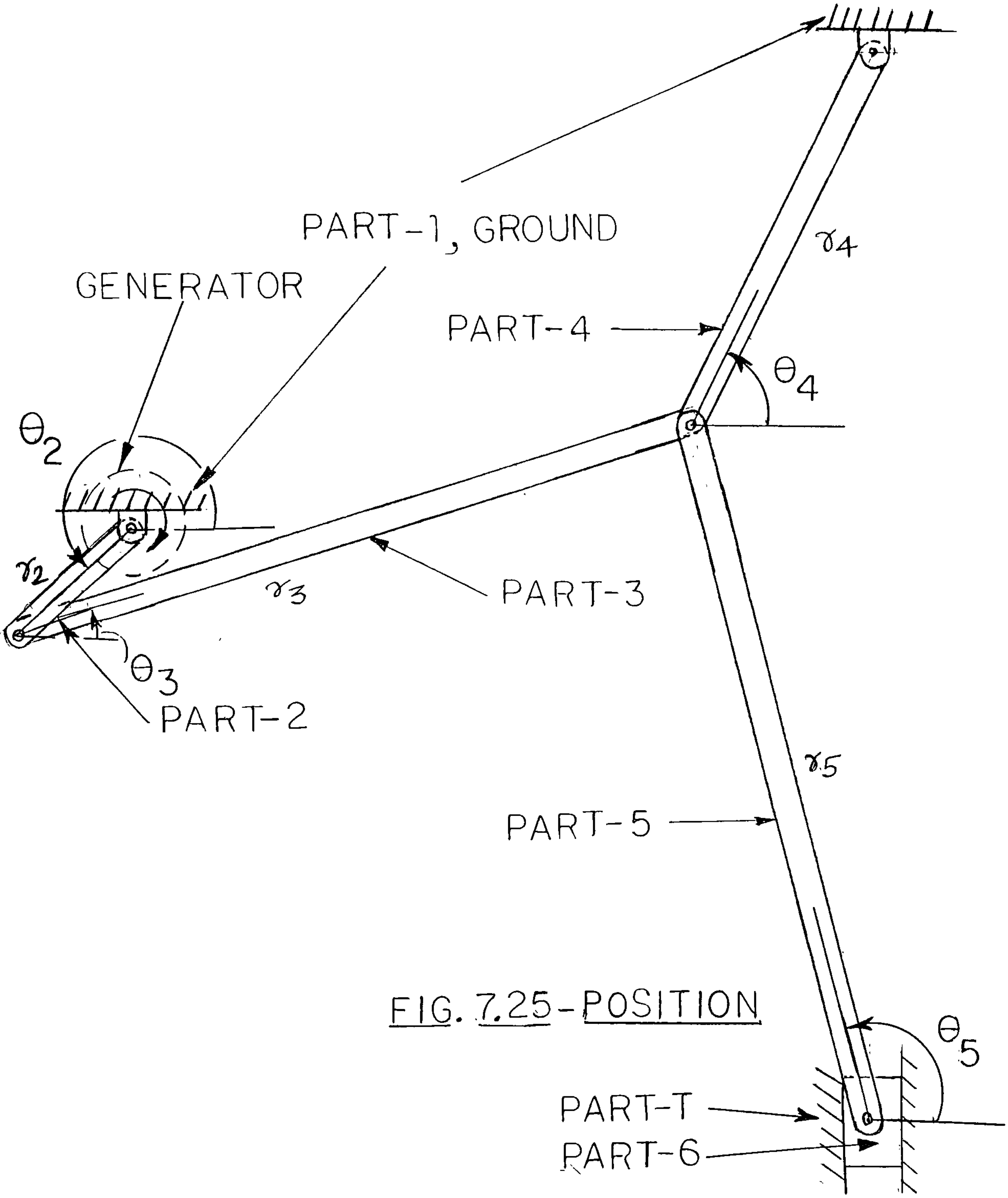


FIG. 7.25-POSITION

TOGGLE MECHANISM

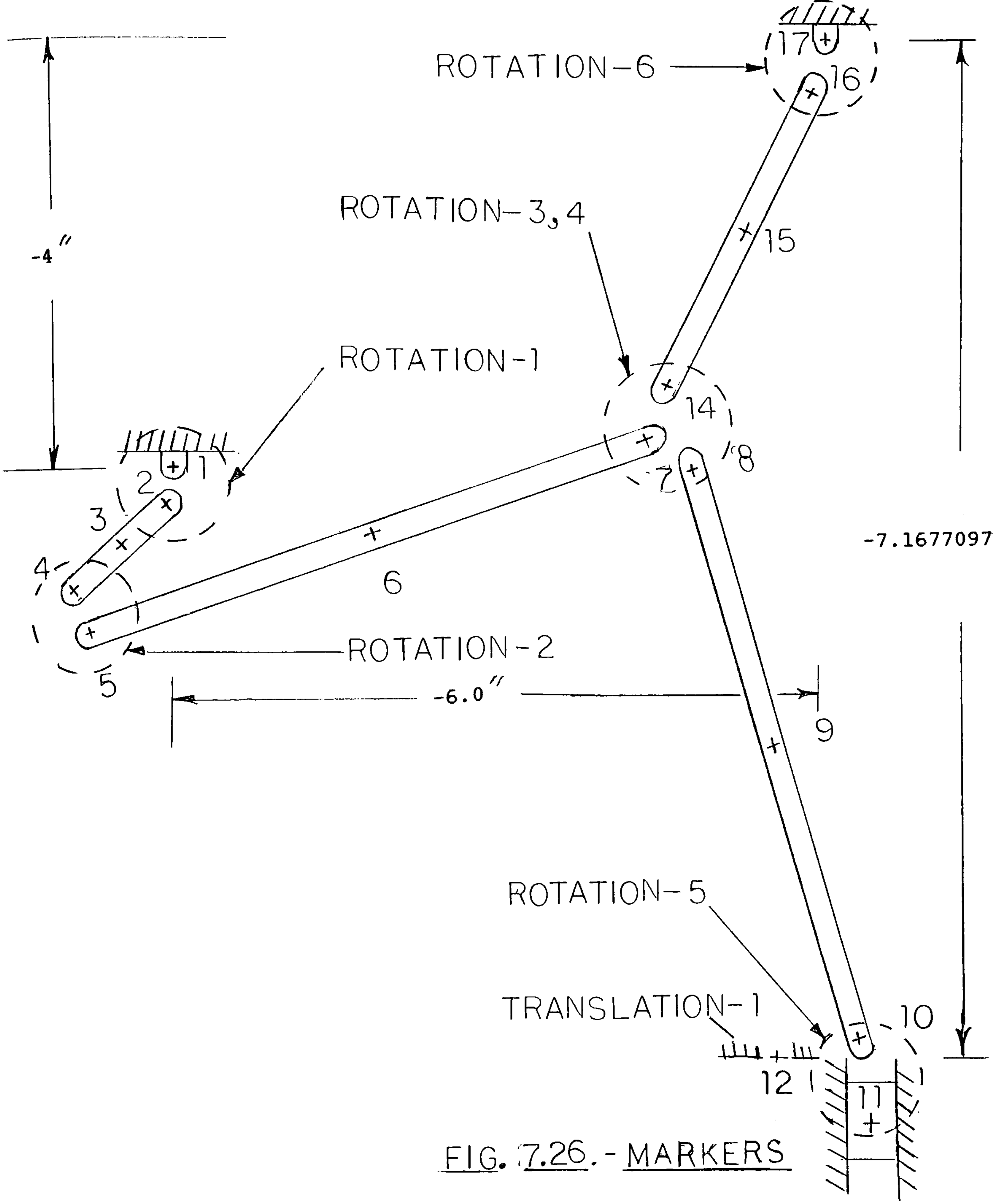


FIG. 7.26. - MARKERS

TOGGLE MECHANISM

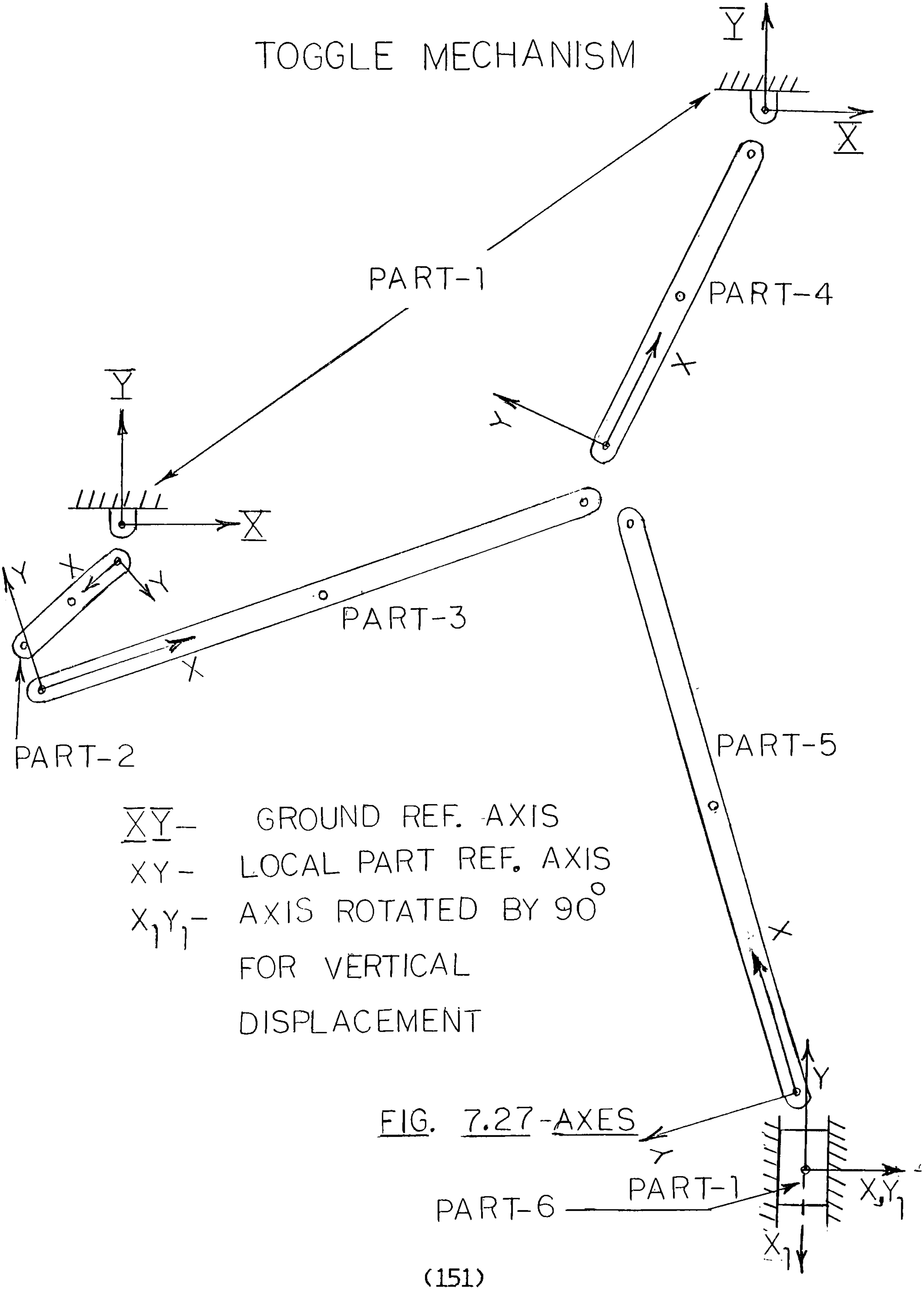


FIG. 7.27-AXES

ABBREVIATIONS

THIS EXAMPLE ILLUSTRATES HOW TO ABBREVIATE THE VARIOUS DRAM STATEMENTS IN THE INPUT DATA CODING. ABBREVIATIONS ARE GIVEN AS FOLLOWS:

PA= PART,GR= GROUND,MA= MARKER,AN OR A= ANGLE,MA= MASS,
IN= MASS MOMENT OF INERTIA,DE= DEGDANGLE,GM= GMARKER,
PO= POINT,RO= ROTATION,TR= TRANSLATION,GE= GENERATOR,
CO= CONSTANT VELOCITY,SY= SYSTEM,OUT= OUTPUT,
REQ= REQUEST,DIS= DISPLACEMENT,VEL= VELOCITY,
ACC= ACCELERATION.

TOGGLE MECHANISM

```
PA/1,GR
MA/17,GM,PA=1,X=0,Y=0,AN=0
MA/1,GM,PA=1,X=-6.0,Y=-4,AN=0
MA/12,PO,PA=1,X=0,Y=-7.1677097,AN=-90

PA/2,MA,CM=3,IN,AN=225
PA/2,DE=-180.0
     MA==> MASS OF PART 2 IS CONSIDERED AS A ZERO BY DRAM.
     IN==> MASS MOMENT OF INERTIA OF PART 2 IS CONSIDERED
     AS A ZERO BY DRAM. HOWEVER FOR FORCE ANALYSIS, THE
     MASS AND MASS MOMENT OF INERTIA EACH PART MUST BE
     SPECIFIED.
MA/2,GM,PA=2,X=0,Y=0,AN=0
MA/3,PO,PA=2,X=0.5,Y=0
MA/4,PO,PA=2,X=1.0,Y=0

PA/3,MA,CM=6,IN,AN=14
MA/5,GM,PA=3,X=0,Y=0,AN=0
MA/6,PO,PA=3,X=2.5,Y=0
MA/7,PO,PA=3,X=5.0,Y=0

PA/4,MA,CM=16,IN,AN=62
MA/14,GM,PA=4,X=0,Y=0,AN=0
MA/15,PO,PA=4,X=2.0,Y=0
MA/16,PO,PA=4,X=4.0,Y=0,Y=0

PA/5,MA,CM=9,IN,AN=112
MA/10,GM,PA=5,X=0,Y=0,AN=0
MA/9,PO,PA=5,X=2.5,Y=0
MA/8,GM,PA=5,X=5.0,Y=0,AN=0

PA/6,MA,CM=11,IN,AN=0
MA/11,GM,PA=6,X=0,Y=0,AN=-90

RO/1,1,2
     THERE THREE NUMBERS.
     FIRST #1 ==> ROTATIONAL CONTACT IDENTIFICATION NUMBER.
     SECOND #1 ==> I=1
     THIRD #2 ==> J=2
RO/2,4,5
     #2 ==> ROTATIONAL CONTACT IDENTIFICATION NUMBER.
     #4 ==> I=4
     #5 ==> J=5
     THE REST OF ALL ROTATIONAL CONTACTS FOLLOW THE SAME PATTERN.
RO/3,7,8
RO/4,8,14
RO/5,10,11
RO/6,17,16

TR/1,11,12,TRANS=1
     #1 ==> TRANSLATIONAL CONTACT IDENTIFICATION NUMBER.
    #11 ==> I=11
    #12 ==> J=12

GE/1,RO,ON=2,CO,DE=-180.0,PAR=225.0D

SY/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC
```

```
OUT/END=2,STEPS=30,NOPLOT

REQ/1,DIS,11,12
     HERE I=11 & J=12

REQ/2,VEL,11,12
     HERE I=11 & J=12

REQ/3,ACC,11,12
     HERE I=11 &J=12
```

*** NOTE ***

THE INITIAL ANGULAR VELOCITY OF PART 2 IS SUPPLIED IN THE PROGRAM. THE INITIAL ANGULAR VELOCITIES OF ALL OTHER PARTS NEED NOT BE SUPPLIED.

SOME OF THE OUTPUTS ARE NOT ENCLOSED DUE TO THE LIMITED AMOUNT OF SPACE AVAILABILITY.

```
END
```

OUTPUTS

Output comments are the same as example 7.2 . Since STEPS are 30 in the output statement, 30 values are plotted.

TOGGLE MECHANISM

```
-- DEFAULT VALUE (TSM1) -- SYSTEM/TS= 6.6667E-02

SYSTEM HAS    0 DEGREE(S) OF FREEDOM
SYSTEM WILL BE SIMULATED IN KINEMATIC MODE


*---- INPUT DATA LOOP CLOSURE CHECK  ----*
I---------------------------------------I
I ROTATION I DISPLACEMENT I   VELOCITY   I
I          I    ERROR     I    ERROR     I
I----------I--------------I--------------I
I        5 I  4.85328D-03 I  0.00000D+00 I
I        3 I  4.08832D-02 I  3.14159D+00 I
I----------I--------------I--------------I


LOOP CLOSURE DISPLACEMENT SOLUTION

CONVERGENCE WITHIN   2.28101D-16 IN  4 ITERATIONS

LOOP CLOSURE VELOCITY SOLUTION


CORRECTED INITIAL CONDITIONS


PART/     1    0.000000000000000D+00 DEG    0.000000000000000D+00 RAD/SEC
PART/     2    2.250000000000000D+02 DEG   -3.141592653589793D+00 RAD/SEC
PART/     3    1.337803160752009D+01 DEG   -2.505678229946768D-01 RAD/SEC
PART/     4    6.256798043481096D+01 DEG   -5.440674854476506D-01 RAD/SEC
PART/     5    1.116266322837430D+02 DEG    4.155669065973214D-01 RAD/SEC
TRAN/     1    1.030548928346651D+00       -1.768398388055794D+00

KFLAG= 0 ORDER= 0 IFCT=   31 H= 0.66667D-01 ITER=    4


IN THE OUTPUT PHASE  1714 WORDS OF MEMORY WERE REQUIRED
```

TOGGLE MECHANISM

REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR DISPLACEMENT OF MARKER 11 RELATIVE TO MARKER 12	ANGLE (DEGREES)	MAGNITUDE OF THE ANGULAR DISPLACEMENT (DEGS) OF MARKER 11 RELATIVE TO MARKER 12
0.0000E+00	1.03055E+00	2.70000E+02	0.00000E+00
6.6667E-02	9.28158E-01	2.70000E+02	0.00000E+00
1.3333E-01	8.62780E-01	2.70000E+02	0.00000E+00
2.0000E-01	8.38828E-01	2.70000E+02	0.00000E+00
2.6667E-01	8.55057E-01	2.70000E+02	0.00000E+00
3.3333E-01	9.06336E-01	2.70000E+02	0.00000E+00
4.0000E-01	9.85647E-01	2.70000E+02	0.00000E+00
4.6667E-01	1.08545E+00	2.70000E+02	0.00000E+00
5.3333E-01	1.19828E+00	2.70000E+02	0.00000E+00
6.0000E-01	1.31691E+00	2.70000E+02	0.00000E+00
6.6667E-01	1.43428E+00	2.70000E+02	0.00000E+00
7.3333E-01	1.54366E+00	2.70000E+02	0.00000E+00
8.0000E-01	1.63899E+00	2.70000E+02	0.00000E+00
8.6667E-01	1.71561E+00	2.70000E+02	0.00000E+00
9.3333E-01	1.77111E+00	2.70000E+02	0.00000E+00
1.0000E+00	1.80607E+00	2.70000E+02	0.00000E+00
1.0667E+00	1.82411E+00	2.70000E+02	0.00000E+00
1.1333E+00	1.83088E+00	2.70000E+02	0.00000E+00
1.2000E+00	1.83224E+00	2.70000E+02	0.00000E+00
1.2667E+00	1.83229E+00	2.70000E+02	0.00000E+00
1.3333E+00	1.83192E+00	2.70000E+02	0.00000E+00
1.4000E+00	1.82850E+00	2.70000E+02	0.00000E+00
1.4667E+00	1.81663E+00	2.70000E+02	0.00000E+00
1.5333E+00	1.78956E+00	2.70000E+02	0.00000E+00
1.6000E+00	1.74093E+00	2.70000E+02	0.00000E+00
1.6667E+00	1.66641E+00	2.70000E+02	0.00000E+00
1.7333E+00	1.56514E+00	2.70000E+02	0.00000E+00
1.8000E+00	1.44066E+00	2.70000E+02	0.00000E+00
1.8667E+00	1.30133E+00	2.70000E+02	0.00000E+00
1.9333E+00	1.15967E+00	2.70000E+02	0.00000E+00
2.0000E+00	1.03055E+00	2.70000E+02	0.00000E+00

CHAPTER 8 : COMPUTER GRAPHICS ON THE VAX/VMS SYSTEM

8.1 INTRODUCTION TO GRAPHICS:

This graphics chapter describes how to start DRAM's GRAPHICS on the VAX/VMS system at RIT. The most common commands which are used for graphics have been explained in this chapter.

The plotting of output request graphs has also been explained along with a sample example.

8.2 PLOTTING GRAPHS:

Commands for plotting graphs are given in the section: "Getting started with the DRAM's graphics on the VAX/VMS at RIT". However, some additional information has been explained here which will be useful for plotting graphs.

1. DRAM writes the name of program at the top of the graph page which is exactly the same as the written name in the input data program.
2. At the bottom of the graph page, there are three lines. These lines describe the graph. The description of terminology is as follows:

   1. PLOT NO =1
   2. REQ # ==> Request number
   3. X-AXIS TYPE ==> Describes the values to be plotted on the x-axis.

4. I==> Marker identification number.

5. J==> Marker identification number.

Note: If the x-axis type is TIME, then the columns REQ, COMP, I and J will be blank.

6. REQ# ==> Request number.

7. COMP ==> Component.

8. Y-AXIS TYPE ==> Describes the values to be plotted on the y-axis.

9. I ==> Marker identification number.

10. J ==> Marker identification number.

11. RUN ==> Run number.

12. FILE ==> DRAM reads the graphics request from this file.

For Example:

See the first graph of graphics example (9.5). The ploted graph is displacement vs time. This plot is a result of REQUEST/1, and is the displacement of marker 20 (I=20) with respect to marker 10 (J=10). The request file has been read from file 12. The file 12 is created in DRAM software. The RUN number is 1. The PLOT number is also 1.

GETTING STARTED WITH DRAM GRAPHICS ON THE VAX/VMS'S VT-240 TERMINAL AND TEKTRONIX-4114 SERIES TERMINAL AT RIT

DRAM software is available on the VAXC system only. DRAM is capable of running DRAM GRAPHICS on the Tektronix 4114 series/VT-240 (Tektronix 4010 mode) terminals.

SETTING OF THE VT-240 TERMINAL:-

For the DRAM GRAPHICS, the terminal VT-240 must be in the graphics mode. Setting of the VT-240 terminal in the graphics mode is done as follows:

1. Hit set up key of the VT-240 terminal. The screen will display various messages at bottom of the screen.
2. Move the cursor by means of the arrow keys on "GENERAL". Then hit "ENTER" key located at lower right corner of the key board.

3. The screen will display various new messages at the bottom of the screen. Move the cursor on the "VT200 MODE, 7 BIT CONTROLS". Then hit the "ENTER" key. The screen will display " 4010/4014 MODE".

4. Now hit the set up key. This completes the setting of THE VT-240 terminal for the graphics.

SETTING OF THE TEKTRONIX-4114 SERIES TERMINAL:-

As the Tektronix-4114 series terminal is a graphics terminal, it does not need major terminal settings for the graphics. There is only one command that needs to be typed after the $ sign before starting the DRAM graphics:

$SET TERM/SCOPE

This command must be typed during every log-in on the system. However, this command can be put in the LOGIN.COM file so that, it need not be typed at all. This completes the minor adjustment of the Tektronix-4114 series terminal.

TYPES OF FILES TO BE USED FOR GRAPHICS:-

Once the selection of the terminal is done, the following files need to be used depending on the requirements. There are two files:

1. Graphics File ===> produces the graphics on the screen.

For Example: sixbar.gra

The file type [.gra] identifies the graphics file. The graphics file is created by using the "GRSAVE" keyword in the input data language program (DRAM's main data program).

2. Request File ===> produces the plot (graph) of output requests (plot of displacement Vs time etc.).

For Example: sixbar.req

The file type [.req] identifies the request file. The request file is created by using the "SAVEINT" keyword in the input data language program (DRAM's main data program).

After specifying this important information, graphics can be started.

GETTING STARTED COMMANDS:-

Type 'DRAPP' after $ sign.

For Example:

$DRAMPP then hit <cr>, where <cr> ===> indicates a carriage return The following message will display on the screen.

"Number of request files (<cr>=0)":

For Example:

Number of request files (<cr>=0): 1 then hit <cr>.

where if <cr>=0 means there is no request file. 1 means there is one request file.

After hitting the carriage return, the following message will display on the screen.

"Request file name (<cr>=none)":

For example:

Request file name(<cr>=none)= sixbar.req

The file type [.req] does not have to be typed (printed). It is optional.

Note: It is not necessary to use the request file if the plotting graphs of the output request are not required.

After hitting the carriage return, the following message will be displayed on the screen.

"Number of graphics files (<cr>=0)":

For Example:

Number of graphics files (<cr>=0)= 1 then hit <cr>.

After hitting the carriage return, the next message on the screen will be

"Graphics file name (<cr>=none)":

For Example:

Graphics file name (<cr>=none)= sixbar.gra then hit <cr>.

The file type [.gra] does not have to be typed (printed). It is optional.

After the carriage return, the screen will display the following message.

"Enter command file name (<cr>=none)":

It is not necessary to use this command. Just hit <cr> and the screen will display the following message.

"Enter baud rate":

For Example:

Enter baud rate = 4800 then hit <cr>. ===> for the

VT-240 (Tektronix 4010 mode) terminal only.

Enter baud rate = 1200 then hit <cr>. ===> for the Tektronix-4114 series terminal only.

The next message on the screen will be

"Enter command"

The cursor will keep flashing on the next line without $ sign.

Type READ G=11 R=12

For Example:

READ G=11 then hit <cr>. (If the graphics is needed only)

READ R=12 then hit <cr>. (If the plotting graph is needed only.)

READ G=11 R=12 then hit <cr>. (For both)

Note: This command must be typed in the upper case letters with the single spacing between each word. DRAM does not accept lower case letters. The "READ" command must be the first command entered after the screen displays the "Enter Command" message.

G=11 ===> Reads the graphics file. In absence of G=11, DRAM will still display graphics on the screen. So G=11 may not not need to type after READ.

R=12 ===> Reads the request file and R=12 must be typed if the plotting graphs of output request is needed.

From this point onward the graphics commands and the plotting graph commands need to be considered separately.

Commands for graphics:

After hitting the carriage return (READ G=11 <cr>), the screen will display the mechanism of system. The mechanism can be superpositioned by typing SUPERPOSITION after the Enter Command message.

SUPERPOSITION then hit <cr>.

After hitting the carriage return, the cursor will keep flashing on the first letter of the SUPERPOSITION. It does not move to the next line. The command SUPERPOSITION can be abbreviated to SUP.

Now type command DISPLAY

DISPLAY then hit <cr>.

After hitting the carriage return, the screen will display the superpositioned mechanism. The command DISPLAY can be abbreviated to DIS. If the displayed mechanism does not fit on the screen, then use the following command after the Enter Command message.

SET SCALE=.5 then hit <cr>.

This command will reduce the original size of mechanism by half. The original size can be reduced to 3/4 by putting .75 number instead of .5. Care should be taken that the SET SCALE Command reduces the previous size by the assigned new number of SET SCALE every time. After the carriage return, type SUPERPOSITION which is followed by DISPLAY. Once the screen displayed the mechanism on the screen, a hard copy of the mechanism can be obtained by simply pressing the hard copy/print screen key. This completes the graphics. Now consider the plotting graphs of the output request .

Commands for the plotting GRAPHS:

After the carriage return (READ R=12), the screen will display the Enter Command message. Now type the following command.

PLOT XAXIS=Type YAXIS=Type ID

then hit <cr>.

For Example:

PLOT XAXIS=TIME YAXIS=MAG 1 then hit <cr>.

Each word of the command must be separated by a single spacing. The graph will be plotted as a magnitude (MAG) of request 1 vs time. A angular component of the request can be plotted by typing "A" instead of MAG. A hard copy of graph can be obtained by the pressing hard copy/print screen key.

CHAPTER 9: COMPUTER GRAPHIC PROGRAMS

Computer graphics need to be done by writing a graphic program in DRAM's input data coding (program). DRAM input data coding must contain the GRSAVE and SAVEINT in the OUTPUT statements. The function of GRSAVE and SAVEINT has already been explained in chapter 4. Since graphics depend on DRAM's input data coding, the graphic program must be coded after the input data coding (program).

9.1 SLENDER ROD (REFER TO EXAMPLE 7.1 OF CHAPTER 7.)

LIST

```
PART/1,GROUND
MARKER/10,POINT,PART=1,X=0,Y=0

PART/2,MASS=1.3685894,CM=30,INERTIA=11.010755,ANGLE=-45
MARKER/20,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/30,POINT,PART=2,X=2.4583333,Y=0
MARKER/40,POINT,PART=2,X=4.9166667,Y=0

ROTATION/1,I=10,J=20

SYSTEM/GC=1,JGRAV=-32.2,ERR=1.E-4,IC

OUTPUT/END=2.5,STEPS=50,GRSAVE,SAVEINT
      SAVEINT==> SAVES THE REQUEST INFORMATION ON FORTRAN UNIT 12
      WHICH IS USED FOR PLOTTING GRAPHS OF THE OUTPUT REQUESTS.
      GRSAVE==> SAVES THE TEKTRONIX SCHEMATIC INFORMATION FOR THE
      DRAM GRAPHICS. THESE TWO STATEMENTS MUST BE IN THE PROGRAM
      IN ORDER TO RUN THE DRAM GRAPHICS ON THE TEKTRONIX OR VT240
      TERMINAL.

REQUEST/1,DISPLACEMENT,I=40,J=10

REQUEST/2,VELOCITY,I=40,J=10
```

GRAPHICS

DESCRIPTION OF GRAPHICS

THE DOCUMENTATION OF EACH GRAPHIC STATEMENT IS GIVEN AFTER EACH GRAPHIC STATEMENT.

```
GRAPHICS/10,CIRCLE,CM=10,RADIUS=0.0333333
     NUMBER 10 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.0333333 FT. IS DRAWN WITH MARKER 10 AS A CM.
     CM==> TAKES MARKER 10 FOR THE CENTER OF A CIRCLE.
GRAPHICS/20,CIRCLE,CM=20,RADIUS=0.0333333
     NUMBER 20 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.0333333 FT. IS DRAWN WITH MARKER 20 AS A CM.
     CM==> TAKES MARKER 20 FOR THE CENTER OF A CIRCLE.
GRAPHICS/30,CIRCLE,CM=40,RADIUS=0.0333333,SEG=4
     NUMBER 30 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.333333 FT. IS DRAWN WITH MARKER 40 AS A CM.
     CM==> TAKES MARKER 40 FOR THE CENTER OF A CIRCLE.
     SEG==> USES FOUR STRAIGHT LINE SEGMENTS TO DRAW THE CIRCLE.
GRAPHICS/40,OUTLINE=20,40
     NUMBER 40 IS THE GRAPHICS IDENTIFICATION NUMBER.
     OUTLINE==> DRAWS THE VISIBLE LINE FROM MARKER 20 TO MARKER 40.
     A VISIBLE LINE IS DRAWN DUE TO THE COMMA (,)BETWEEN MARKERS
     20 & 40.

END
```

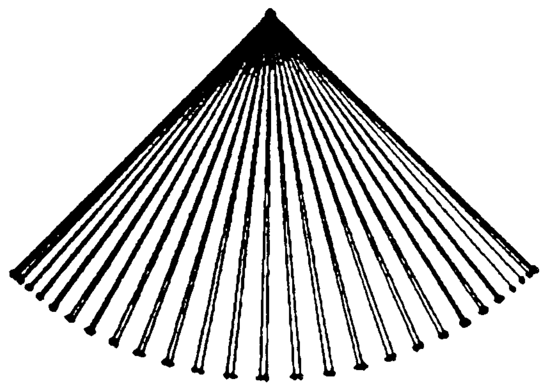


FIG. 9.1

9.2 SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE
(REFER TO EXAMPLE 7.2 OF CHAPTER 7)

```
LIST

PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/11,GMARKER,PART=1,X=0.68346737,Y=0.02522921,ANGLE=0

PART/2,MASS=0.00776398,CM=3,INERTIA=0.00001797,ANGLE=30
,DEGDANGLE=18000
MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/3,POINT,PART=2,X=0.08333333,Y=0
MARKER/4,POINT,PART=2,X=0.16666667,Y=0

PART/3,MASS=0.0310559,CM=6,INERTIA=0.00115021,ANGLE=-5
MARKER/5,GMARKER,PART=3,X=0,Y=0,ANGLE=0
MARKER/6,POINT,PART=3,X=0.3333333,Y=0
MARKER/7,POINT,PART=3,X=0.66666667,Y=0

PART/4,MASS=0.04658385,CM=9,INERTIA=0.00000674,ANGLE=0
MARKER/8,GMARKER,PART=4,X=0,Y=0,ANGLE=0
MARKER/9,POINT,PART=4,X=0.04166667,Y=0
MARKER/10,POINT,PART=4,X=0.08333333,Y=0

ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=7,J=8
TRANSLATION/1,I=8,J=11,TRANSLATION=0.125

FIELD/1,TRANSLATIONAL,CONSTANT,I=10,ANGLE=180,PAR=11.024845

GENERATOR/1,ROTATIONAL,ON=2,CONSTANT VELOCITY,DEGPAR=18000,PAR=30.0D

SYSTEM/GC=1,JGRAV=-32.2,ERR=1.E-4,IC

OUTPUT/END=0.02,STEPS=20,RANGLE,NOPLOT,SAVEINT,GRSAVE
     SAVEINT==> SAVES THE REQUEST INFORMATION ON FORTRAN UNIT 12
     WHICH IS USED FOR PLOTTING GRAPHS OF THE OUTPUT REQUESTS.
     GRSAVE==> SAVES THE TEKTRONIX SCHEMATIC INFORMATION FOR THE DRAM
     GRAPHICS. THESE TWO STATEMENTS MUST BE IN THE PROGRAM IN ORDER
     TO RUN THE DRAM GRAPHICS ON THE TEKTRONIX OR VT240 TERMINAL.

REQUEST/1,VELOCITY,I=9,J=1
REQUEST/2,VELOCITY,I=6,J=1

REQUEST/3,ACCELERATION,I=5,J=1
REQUEST/4,ACCELERATION,I=9,J=1

REQUEST/5,FORCE,I=8,J=7
```

GRAPHICS

DESCRIPTION OF GRAPHICS

THE DOCUMENTATION OF EACH GRAPHIC STATEMENT IS GIVEN AFTER EACH GRAPHIC STATEMENT.

```
GRAPHICS/5,CIRCLE,CM=1,RADIUS=0.083333333
     NUMBER 5 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
```

```
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 1 AS A CM.
     CM==> TAKES MARKER 1 FOR THE CENTER OF A CIRCLE.
GRAPHICS/10,CIRCLE,CM=11,RADIUS=0.083333333,SEG=3
     NUMBER 10 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 11 AS A CM.
     CM==> TAKES MARKER 11 FOR THE CENTER OF A CIRCLE.
     SEG==> USES THREE STRAIGHT LINE SEGMENTS TO DRAW THE
     CIRCLE ON THE SCREEN.
GRAPHICS/15,CIRCLE,CM=2,RADIUS=0.083333333
     NUMBER 15 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 2 AS A CM.
     CM==> TAKES MARKER 2 FOR THE CENTER OF A CIRCLE.
GRAPHICS/20,CIRCLE,CM=4,RADIUS=0.083333333
     NUMBER 20 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 4 AS A CM.
     CM==> TAKES MARKER 4 FOR THE CENTER OF A CIRCLE.
GRAPHICS/25,OUTLINE=2,4
     NUMBER 25 IS THE GRAPHICS IDENTIFICATION NUMBER.
     OUTLINE==> DRAWS THE VISIBLE LINE FROM MARKER 2 TO MARKER 4.
     A VISIBLE LINE IS DRAWN DUE TO THE COMMA (,) BETWEEN MARKERS
     2 & 4.

GRAPHICS/30,CIRCLE,CM=5,RADIUS=0.083333333
     NUMBER 30 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 5 AS A CM.
     CM==> TAKES MARKER 5 FOR THE CENTER OF A CIRCLE.
GRAPHICS/35,CIRCLE,CM=7,RADIUS=0.083333333
     NUMBER 35 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 7 AS A CM.
     CM==> TAKES MARKER 7 FOR THE CENTER OF A CIRCLE.
GRAPHICS/40,OUTLINE=5,7
     NUMBER 40 IS THE GRAPHICS IDENTIFICATION NUMBER.
     OUTLINE==> DRAWS THE VISIBLE LINE FROM MARKER 5 TO MARKER 7.
     A VISIBLE LINE IS DRAWN DUE TO THE COMMA (,) BETWEEN MARKERS
     5 & 7.

GRAPHICS/45,CIRCLE,CM=8,RADIUS=0.083333333
     NUMBER 45 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 8 AS A CM.
     CM==> TAKES MARKER 8 FOR THE CENTER OF A CIRCLE.
GRAPHICS/50,CIRCLE,CM=9,RADIUS=0.083333333,SEG=3
     NUMBER 50 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 9 AS A CM.
     CM==> TAKES MARKER 9 FOR THE CENTER OF A CIRCLE.
     SEG==> USES THREE STRAIGHT LINE SEGMENTS TO DRAW THE CIRCLE
     ON THE SCREEN.
GRAPHICS/55,CIRCLE,CM=10,RADIUS=0.083333333,SEG=3
     NUMBER 55 IS THE GRAPHICS IDENTIFICATION NUMBER. A CIRCLE
     OF RADIUS=0.083333333 FT. IS DRAWN WITH MARKER 10 AS A CM.
     CM==> TAKES MARKER 10 FOR THE CENTER OF A CIRCLE.
     SEG==> USES THREE STRAIGHT LINE SEGMENTS TO DRAW THE CIRCLE
     ON THE SCREEN.
GRAPHICS/60,OUTLINE=8/9/10
     NUMBER 60 IS THE GRAPHICS IDENTIFICATION NUMBER.
     OUTLINE==> DRAWS THE INVISIBLE LINE AMONG MARKERS 8,9,AND 10.
     A INVISIBLE LINE IS DRAWN DUE TO THE SLASH (/) AMONG MARKERS
     8,9 & 10.

END
```

Slider crank mechanism:

A complete graphic cycle of the slider crank mechanism is shown in the figure 9.2. The graphic cycle starts when the crank is at 30 degrees. Figure 9.2 shows the different positions of the slider as the crank moves to the various angles.

The velocity vs time graph has been plotted in the figure 9.3. The plotted velocity is the velocity of marker 9 with respect to marker 1. The angular acceleration of marker 5 with respect to marker 1 vs time has been plotted in the figure 9.4. The force exerted by marker 7 on marker 8 vs time has been plotted in the figure 9.5. The plotting of graphs has already explained in the chapter 8.

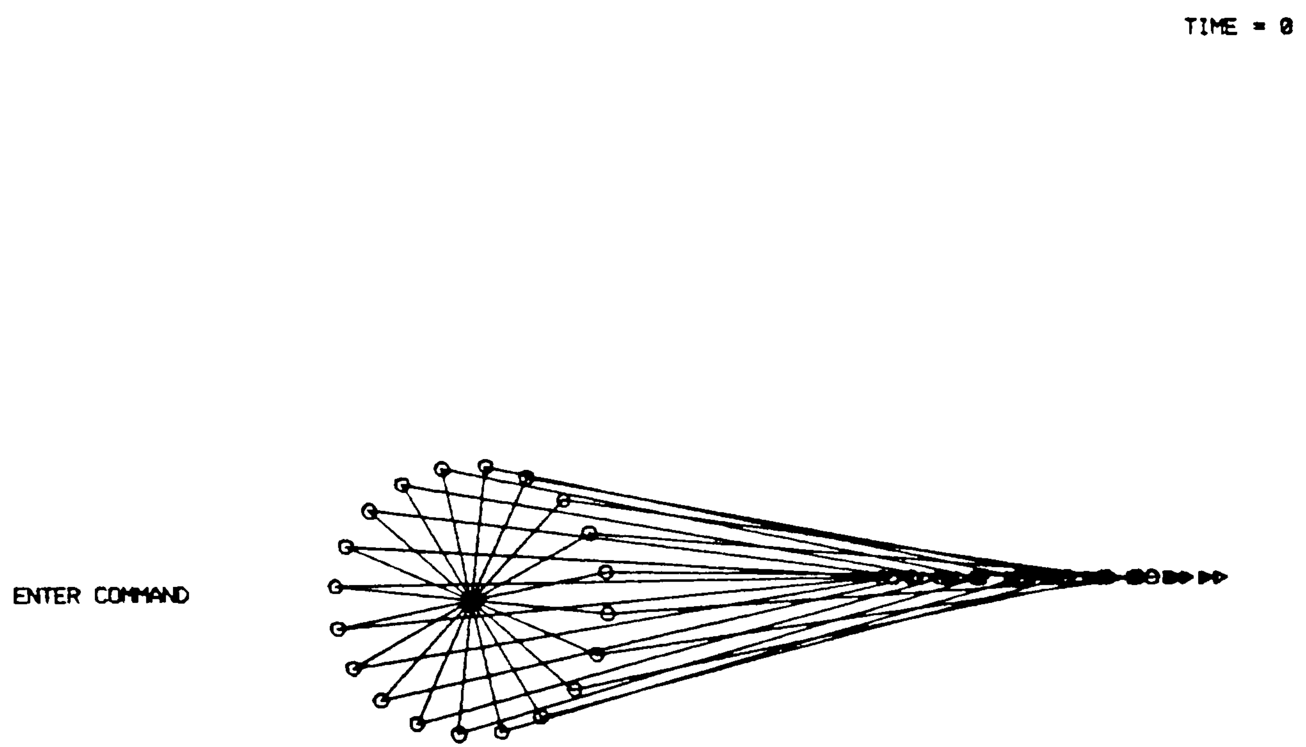


FIG. 9.2

SLIDER CRANK MECHANISM WITH APPLIED TRANSLATIONAL FORCE

ENTER COMMAND

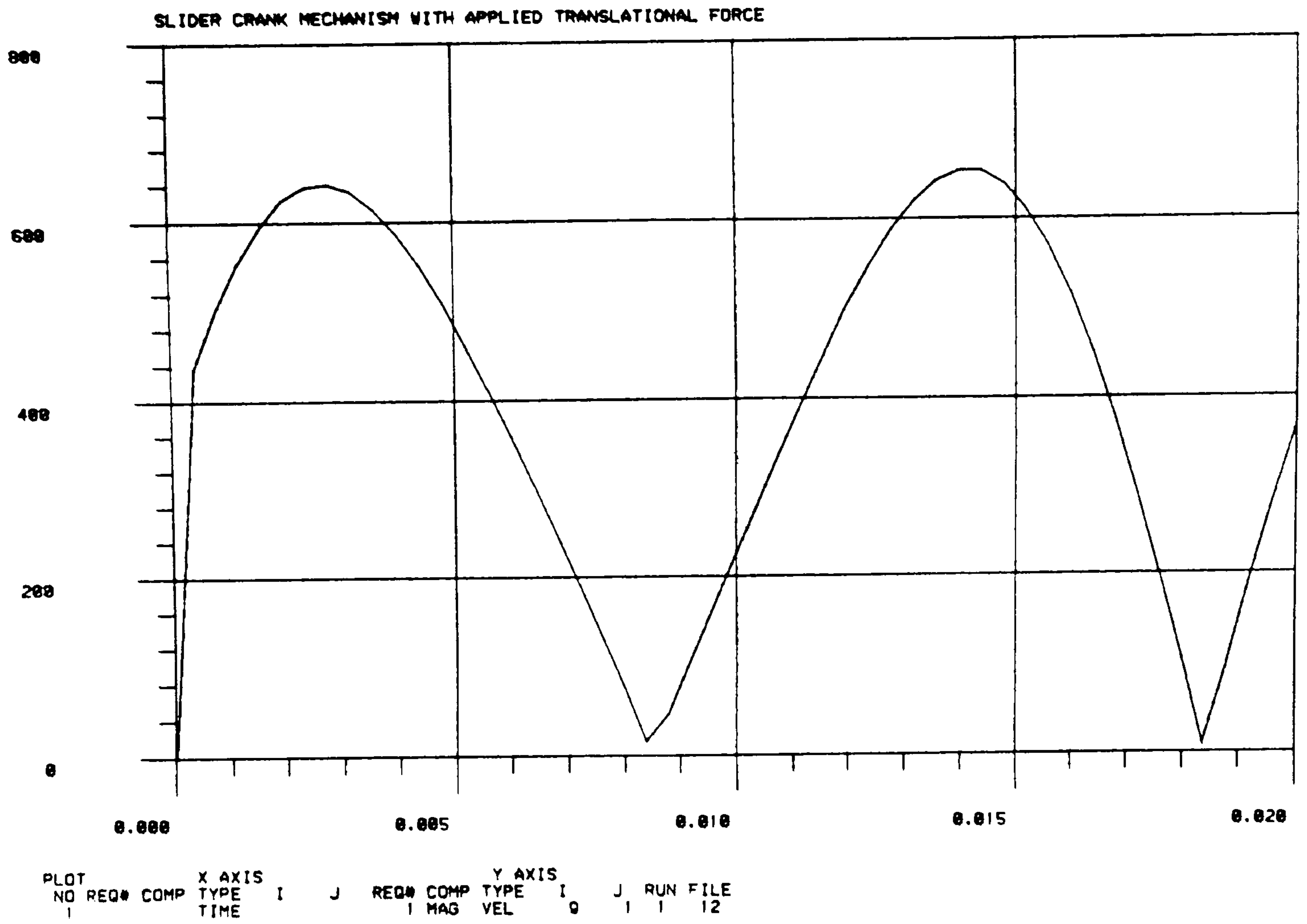


FIG. 9.3 : LINEAR VELOCITY OF SLIDER.

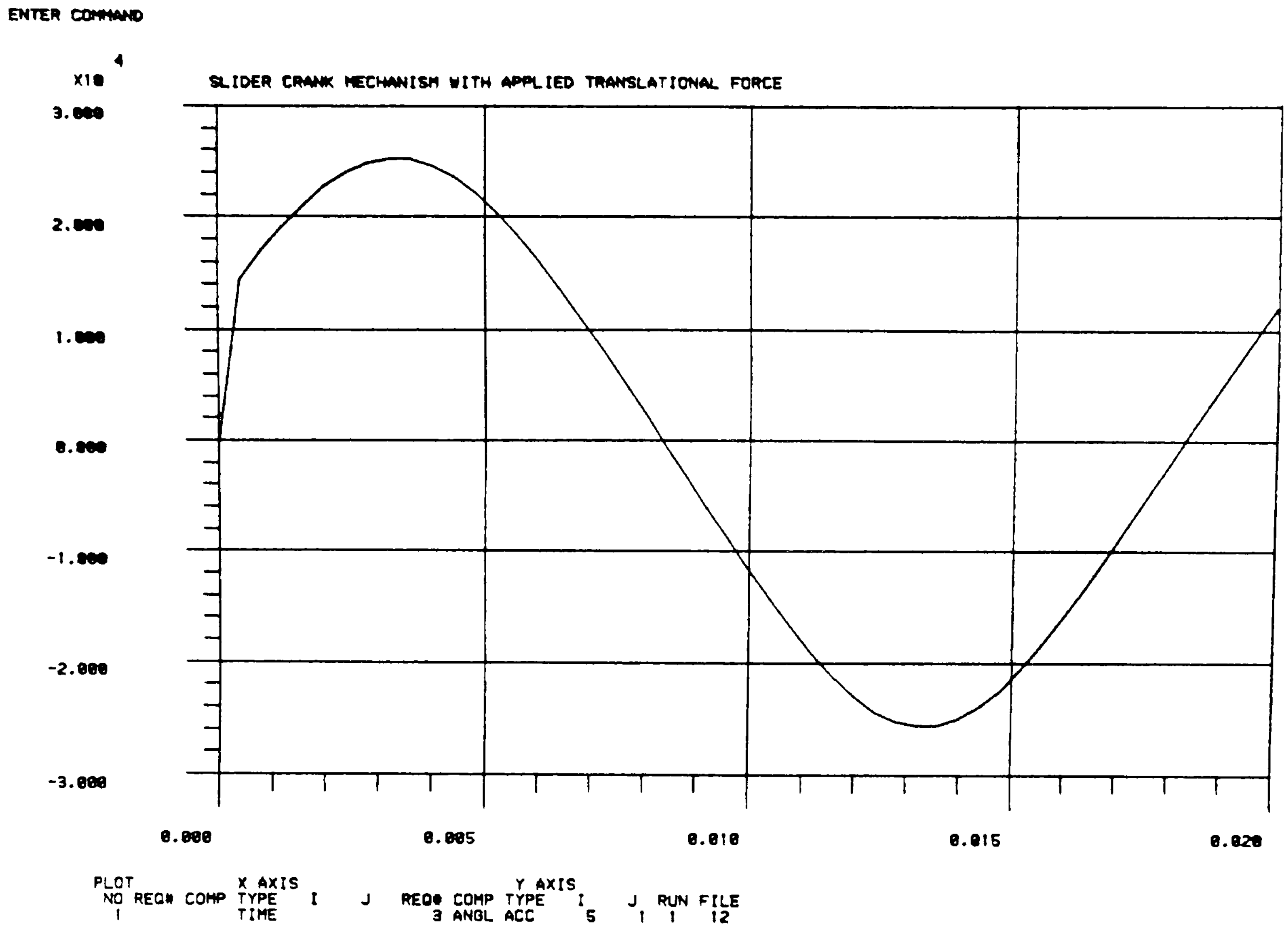


FIG. 9.4 : ANGULAR ACCELERATION OF CONNECTING ROD.

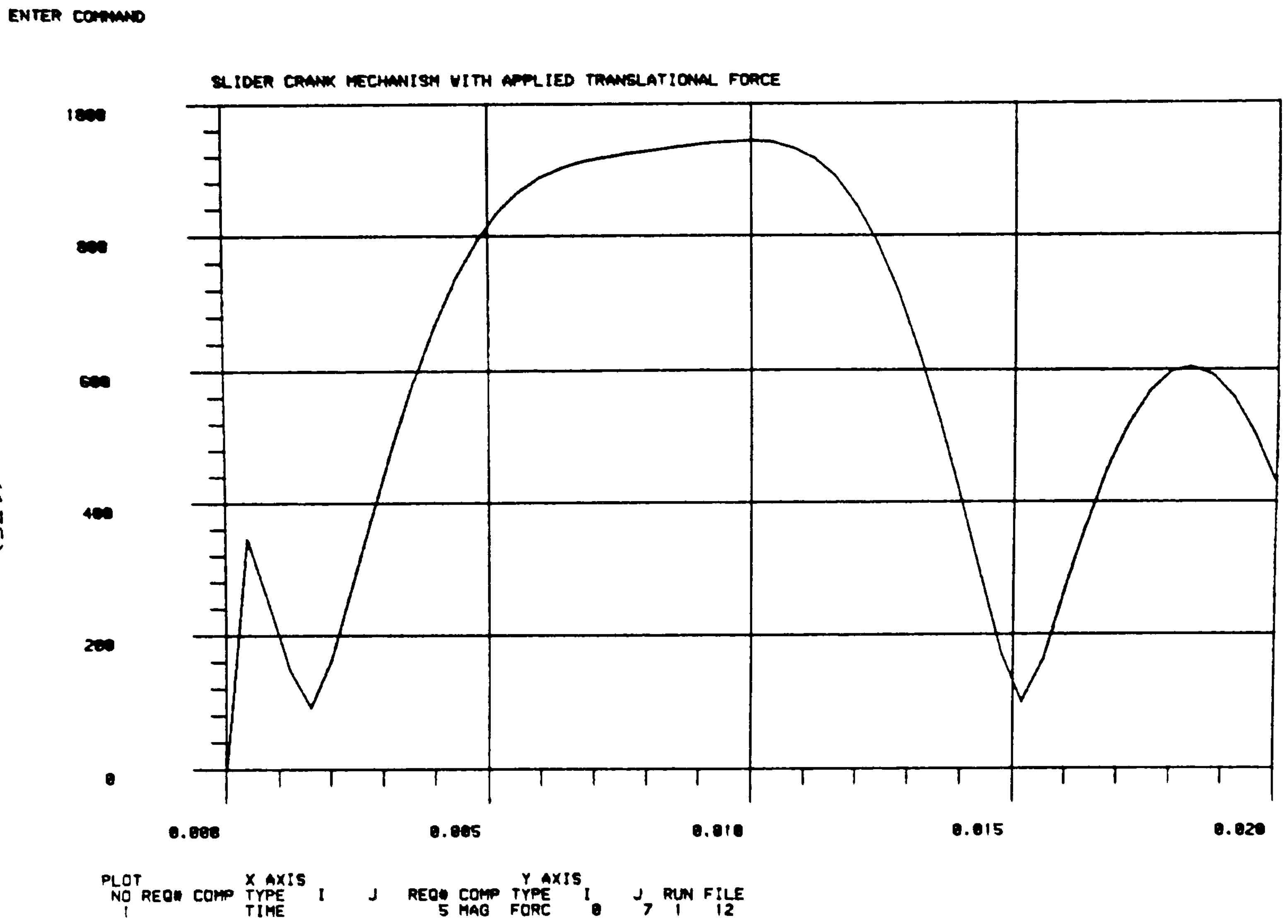


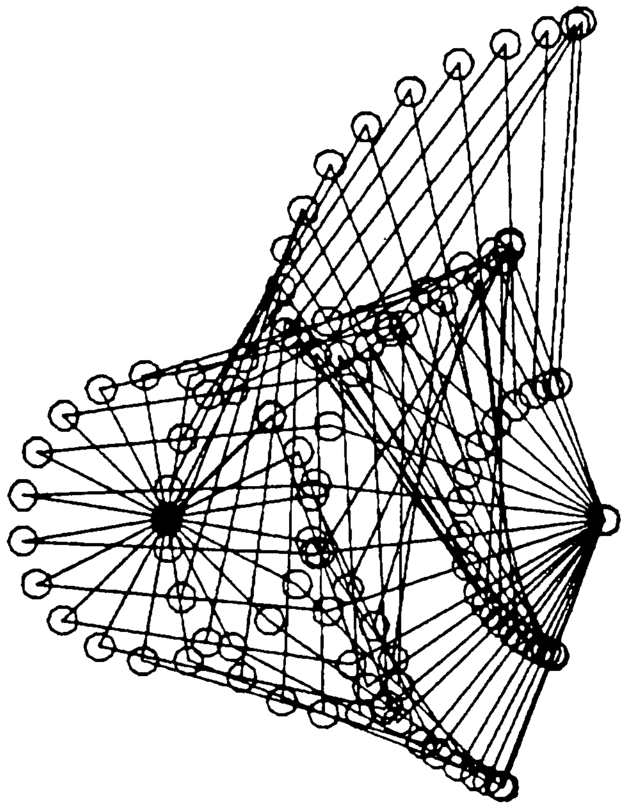
FIG. 9.5 : FORCE EXERTED BY SLIDER ON CONNECTING ROD.

9.3 SIX-BAR LINKAGE MECHANISM [KINEMATIC ANALYSIS]
(REFER TO EXAMPLE 7.5 OF CHAPTER 7.)

```
PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/11,POINT,PART=1,X=2.9965472,Y=0

PART/2,MASS=0.15,CM=3,INERTIA=0.0125,ANGLE=45
PART/2,DEGDANGLE=24000
MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/3,GMARKER,PART=2,X=.5,Y=0,ANGLE=0
MARKER/4,POINT,PART=2,X=1,Y=0

PART/3,MASS=0.3,CM=6,INERTIA=0.1,ANGLE=35
PART/3,DEGDANGLE=-11172.677
MARKER/5,POINT,PART=3,X=0,Y=0
MARKER/6,GMARKER,PART=3,X=1,Y=0,ANGLE=0
MARKER/7,POINT,PART=3,X=2,Y=0

PART/4,MASS=0.3,CM=9,INERTIA=0.1,ANGLE=-71
PART/4,DEGDANGLE=2200.1579
MARKER/8,POINT,PART=4,X=0,Y=0
MARKER/9,GMARKER,PART=4,X=1,Y=0,ANGLE=0
MARKER/10,POINT,PART=4,X=2,Y=0

PART/5,MASS=0.35,CM=13,INERTIA=0.1822917,ANGLE=59
MARKER/12,POINT,PART=5,X=0,Y=0
MARKER/13,GMARKER,PART=5,X=1.25,Y=0,ANGLE=0
MARKER/14,POINT,PART=5,X=2.5,Y=0

PART/6,MASS=0.35,CM=16,INERTIA=0.18229167,ANGLE=-93
MARKER/15,POINT,PART=6,X=0,Y=0
MARKER/16,GMARKER,PART=6,X=1.25,Y=0,ANGLE=0
MARKER/17,POINT,PART=6,X=2.5,Y=0

ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=7,J=8
ROTATION/4,I=10,J=11
ROTATION/5,I=6,J=12
ROTATION/6,I=14,J=15
ROTATION/7,I=17,J=9


GENERATOR/1,ROTATIONAL,ON=2,CONSTVEL,DEGPAR=24000,PAR=45.0D

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.015,STEPS=20,SAVEINT,GRSAVE,NOPLOT,RANGLE


REQUEST/1,DISPLACEMENT,I=14,J=6
REQUEST/2,DIS,I=4,J=1
REQUEST/2,DISPLACEMENT,I=15,J=9

REQUEST/3,VELOCITY,I=7,J=4
REQUEST/4,VELOCITY,I=6,J=1
REQUEST/5,VELOCITY,I=8,J=1
REQUEST/6,VELOCITY,I=9,J=1
REQUEST/7,VELOCITY,I=14,J=6
REQUEST/8,VELOCITY,I=13,J=1
```

```
REQUEST/9,VELOCITY,I=15,J=9
REQUEST/10,VELOCITY,I=16,J=1

REQUEST/11,ACCELERATION,I=5,J=1
REQUEST/12,ACCELERATION,I=6,J=1
REQUEST/13,ACCELERATION,I=8,J=1
REQUEST/14,ACCELERATION,I=9,J=1
REQUEST/15,ACCELERATION,I=8,J=4
REQUEST/16,ACCELERATION,I=14,J=6
REQUEST/17,ACCELERATION,I=13,J=1
REQUEST/18,ACCELERATION,I=16,J=1
REQUEST/19,ACCELERATION,I=15,J=9


                   GRAPHICS

GRAPHICS/1,CIRCLE,CM=1,RADIUS=0.1
GRAPHICS/2,CIRCLE,CM=2,RADIUS=0.1
GRAPHICS/3,CIRCLE,CM=4,RADIUS=0.1
GRAPHICS/4,OUTLINE=2,4

GRAPHICS/5,CIRCLE,CM=5,RADIUS=0.1
GRAPHICS/6,CIRCLE,CM=6,RADIUS=0.1
GRAPHICS/7,CIRCLE,CM=7,RADIUS=0.1
GRAPHICS/8,OUTLINE=5,7

GRAPHICS/9,CIRCLE,CM=11,RADIUS=0.1
GRAPHICS/10,CIRCLE,CM=8,RADIUS=0.1
GRAPHICS/11,CIRCLE,CM=9,RADIUS=0.1
GRAPHICS/12,CIRCLE,CM=10,RADIUS=0.1
GRAPHICS/13,OUTLINE=8,10

GRAPHICS/14,CIRCLE,CM=12,RADIUS=0.1
GRAPHICS/15,CIRCLE,CM=14,RADIUS=0.1
GRAPHICS/16,OUTLINE=12,14

GRAPHICS/17,CIRCLE,CM=15,RADIUS=0.1
GRAPHICS/18,CIRCLE,CM=17,RADIUS=0.1
GRAPHICS/19,OUTLINE=15,17

      *** NOTE ***

      WHILE RUNNING THE DRAM GRAPHICS, MAKE SURE THAT THE STEP
      SIZE IS SMALL. THE MOST COMFORTABLE  STEP SIZE NUMBER WOULD
      BE 20. OTHERWISE, DRAM WILL GIVE THE STACK DUMP OVER FLOW
      MESSAGE.

      THE DESCRIPTION OF THE GRAPHIC STATEMENTS IS GIVEN
      IN THE FIRST TWO EXAMPLES OF THIS SECTION.
END
```

TIME = 0



ENTER COMMAND

SIX BAR LINKAGE MECHANISM [KINEMATIC ANALYSIS]

FIG. 9.6

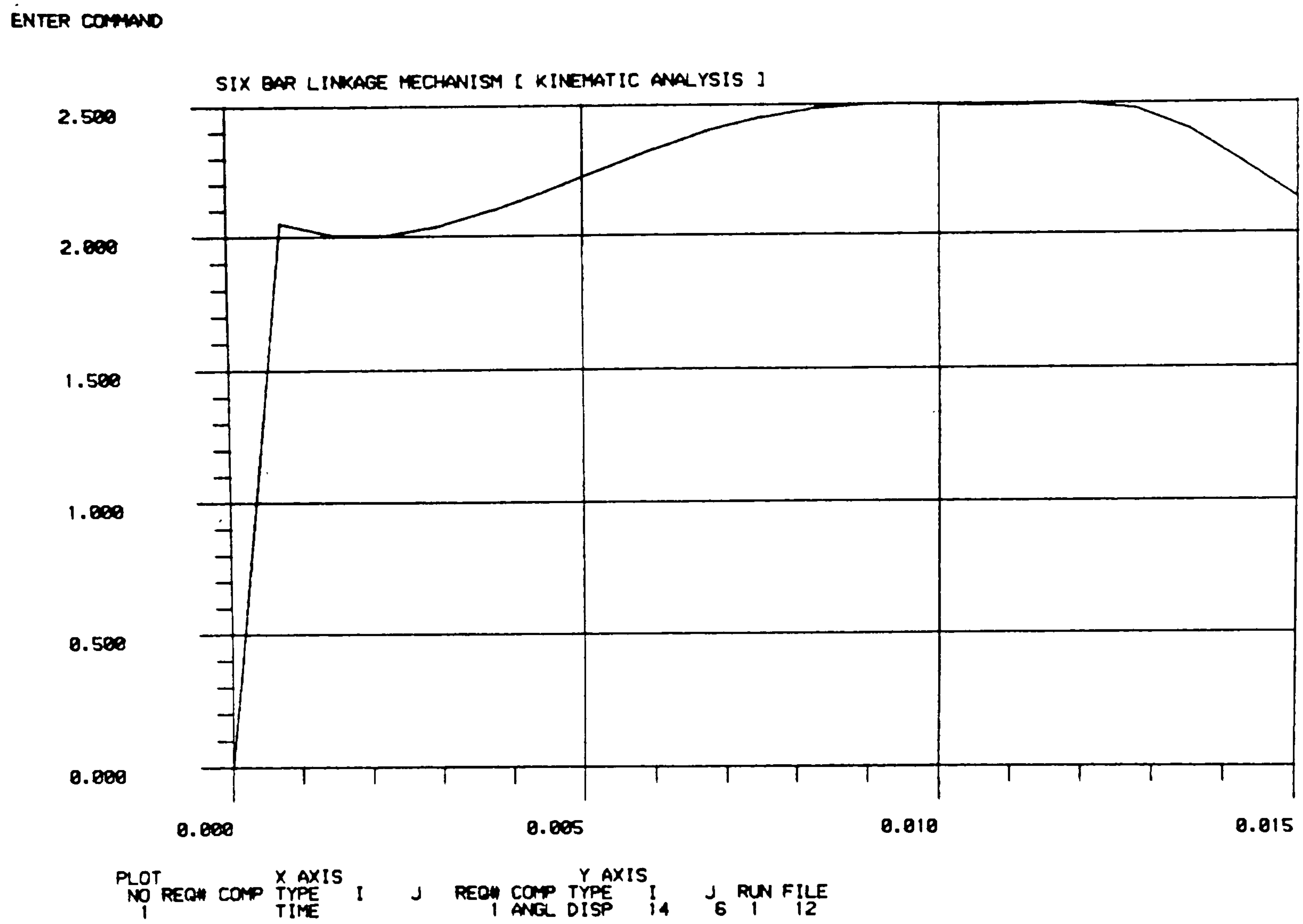


FIG. 9.7 : ANGULAR DISPLACEMENT OF LINK 5.

ENTER COMMAND

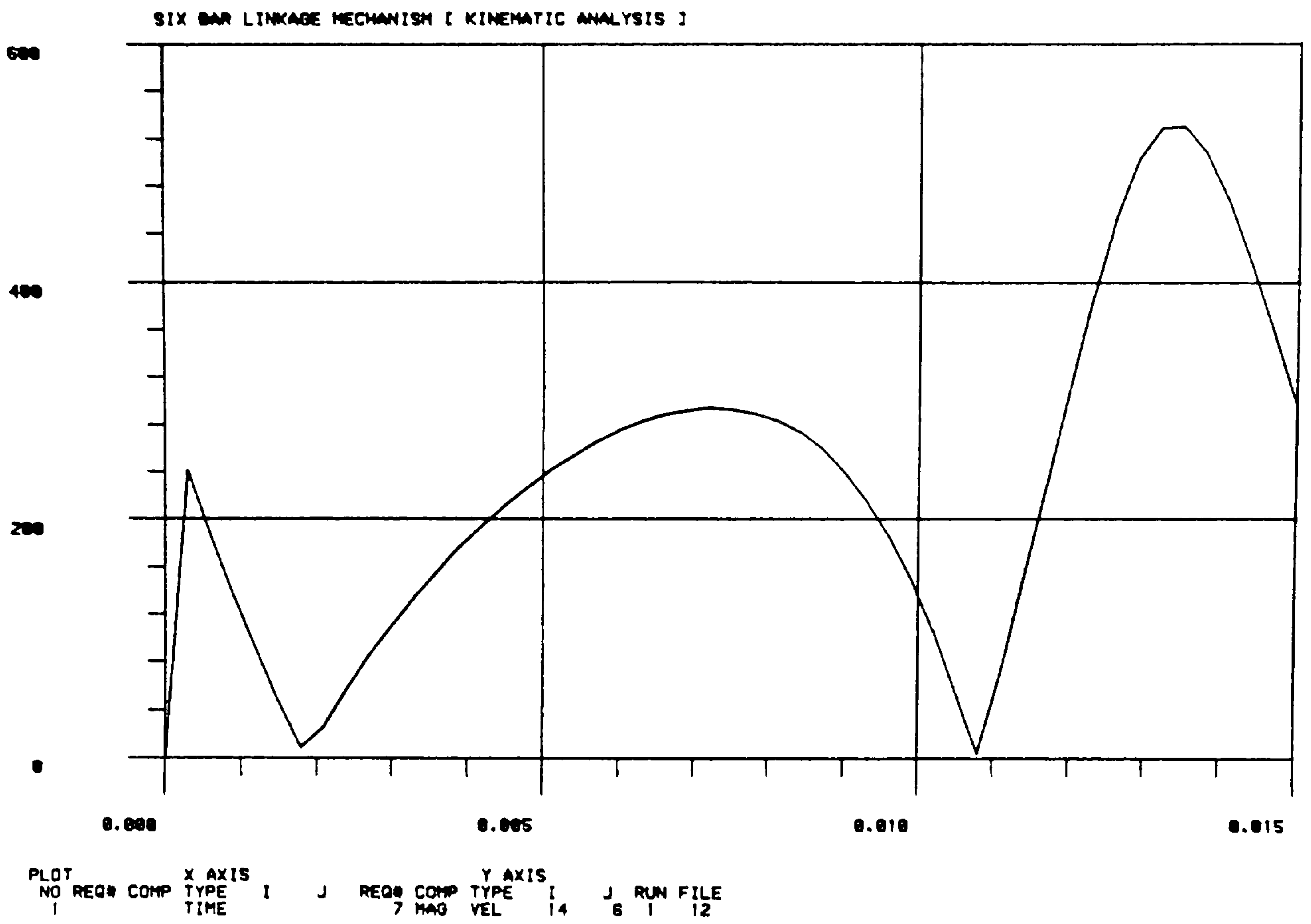


FIG. 9.8 : LINEAR VELOCITY OF LINK 5.

ENTER COMMAND

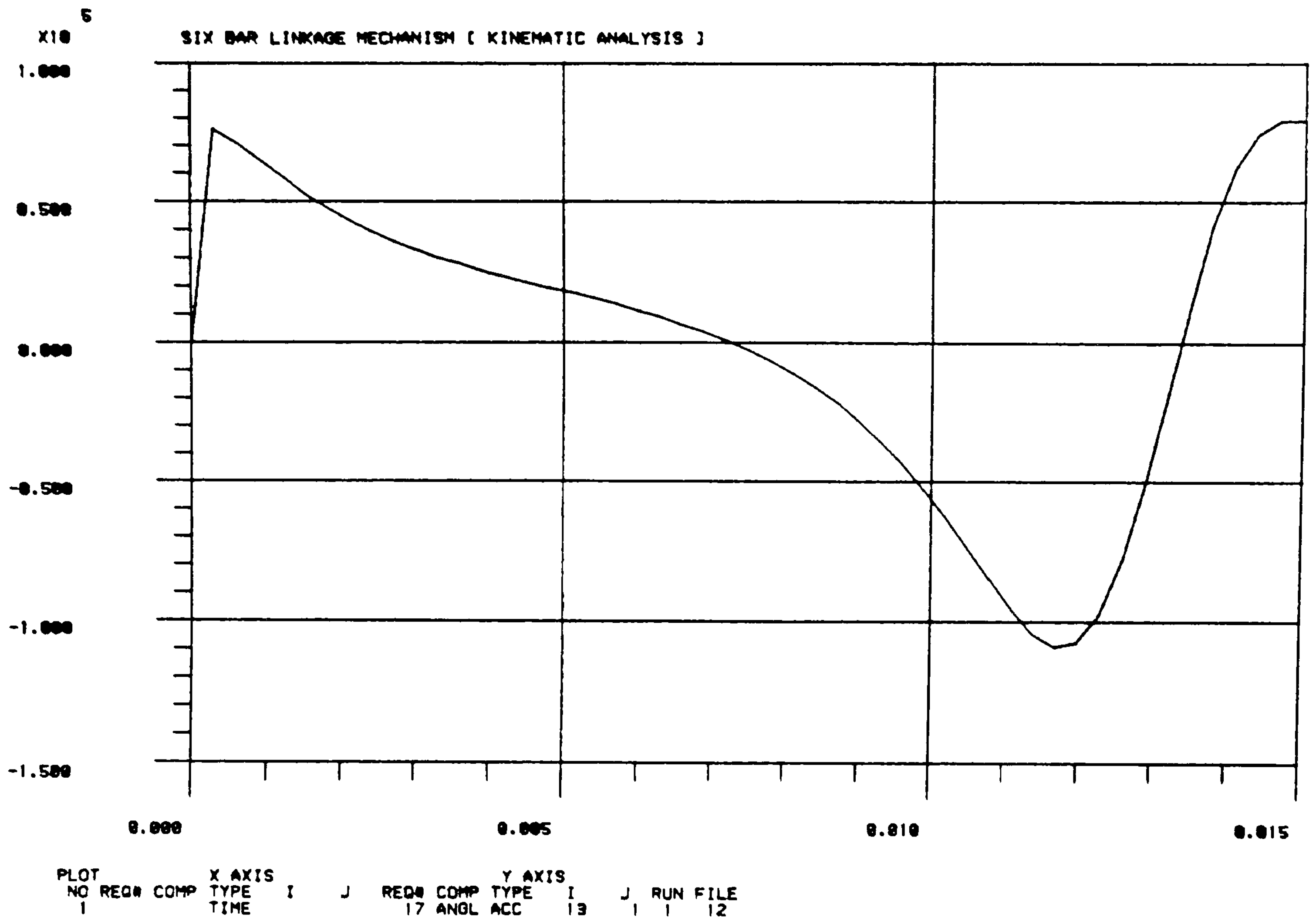


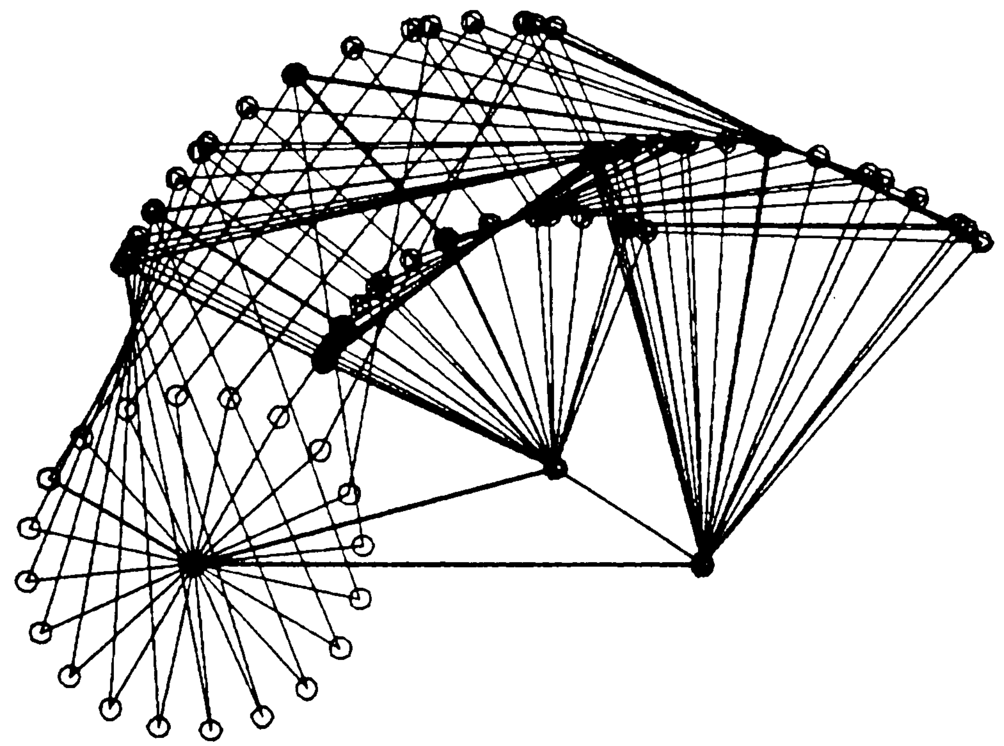
FIG. 9.9 : ANGULAR ACCELERATION OF LINK 5.

9.4 STEPHENSON'S KINEMATIC CHAIN
(REFER TO EXAMPLE 7.6 OF CHAPTER 7.)

```
LIST

PART/1,GROUND
MARKER/1,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/30,POINT,PART=1,X=4.8,Y=0
MARKER/20,GMARKER,PART=1,X=3.4,Y=0.90861048,ANGLE=15.5

PART/2,MASS=0.10,CM=3,INERTIA=0.02133,ANGLE=150
PART/2,DEGDANGLE=24998.149
MARKER/2,GMARKER,PART=2,X=0,Y=0,ANGLE=0
MARKER/3,GMARKER,PART=2,X=0.8,Y=0,ANGLE=0,Y=0
MARKER/4,POINT,PART=2,X=1.6,Y=0

PART/3,MASS=0.60,CM=6,INERTIA=0.968,ANGLE=60
MARKER/5,POINT,PART=3,X=0,Y=0
MARKER/6,GMARKER,PART=3,X=2.25,Y=0,ANGLE=0
MARKER/7,POINT,PART=3,X=4.5,Y=0

PART/4,MASS=0.30,CM=45,INERTIA=0.21796614,ANGLE=-49
MARKER/8,POINT,PART=4,X=0,Y=0
MARKER/9,GMARKER,PART=4,X=2.1,Y=0
MARKER/40,GMARKER,PART=4,X=3.4971568,Y=2.8319418,ANGLE=39
MARKER/45,GMARKER,PART=4,X=1.8,Y=0,ANGLE=27

PART/5,MASS=0.35,CM=11,INERTIA=0.14765,ANGLE=-65
MARKER/10,POINT,PART=5,X=0,Y=0
MARKER/11,GMARKER,PART=5,X=1.2,Y=0,ANGLE=0
MARKER/12,POINT,PART=5,X=2.4,Y=0

PART/6,MASS=0.50,CM=15,INERTIA=0.66666,ANGLE=-97
MARKER/16,POINT,PART=6,X=0,Y=0
MARKER/15,GMARKER,PART=6,X=2,Y=0,ANGLE=0
MARKER/14,POINT,PART=6,X=4,Y=0

ROTATION/1,I=1,J=2
ROTATION/2,I=4,J=5
ROTATION/3,I=7,J=8
ROTATION/4,I=9,J=10
ROTATION/5,I=40,J=16
ROTATION/6,I=12,J=20
ROTATION/7,I=14,J=30


GENERATOR/1,ROTATIONAL,ON=2,CONSTVEL,DEGPAR=24998.149,PAR=150.0D

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.0144,STEPS=20,SAVEINT,GRSAVE,RANGLE


REQUEST/1,DISPLACEMENT,I=15,J=1

REQUEST/2,VELOCITY,I=6,J=1
REQUEST/3,VELOCITY,I=45,J=1
REQUEST/4,VELOCITY,I=11,J=1
REQUEST/5,VELOCITY,I=15,J=1

REQUEST/6,ACCELERATION,I=6,J=1
```

```
REQUEST/7,ACCELERATION,I=45,J=1
REQUEST/8,ACCELERATION,I=11,J=1
REQUEST/9,ACCELERATION,I=15,J=1


                  GRAPHICS

GRAPHICS/50,CIRCLE,CM=1,RADIUS=0.1,SEG=3
GRAPHICS/100,CIRCLE,CM=20,RADIUS=0.1,SEG=3
GRAPHICS/150,CIRCLE,CM=30,RADIUS=0.1,SEG=3
GRAPHICS/200,OUTLINE=1,20,30
GRAPHICS/250,OUTLINE=1,30

GRAPHICS/300,CIRCLE,CM=2,RADIUS=0.1
GRAPHICS/350,CIRCLE,CM=4,RADIUS=0.1
GRAPHICS/400,OUTLINE=2,4

GRAPHICS/450,CIRCLE,CM=5,RADIUS=0.1
GRAPHICS/500,CIRCLE,CM=7,RADIUS=0.1
GRAPHICS/550,OUTLINE=5,7

GRAPHICS/600,CIRCLE,CM=8,RADIUS=0.1,SEG=3
GRAPHICS/650,CIRCLE,CM=9,RADIUS=0.1,SEG=3
GRAPHICS/700,CIRCLE,CM=40,RADIUS=0.1,SEG=3
GRAPHICS/750,OUTLINE=8,9,40
GRAPHICS/800,OUTLINE=8,40

GRAPHICS/850,CIRCLE,CM=10,RADIUS=0.1
GRAPHICS/900,CIRCLE,CM=12,RADIUS=0.1
GRAPHICS/950,OUTLINE=10,12

GRAPHICS/1000,CIRCLE,CM=16,RADIUS=0.1
GRAPHICS/1050,CIRCLE,CM=14,RADIUS=0.1
GRAPHICS/1100,OUTLINE=16,14

      *** NOTE ***

      THE DESCRIPTION OF THE GRAPHICS STATEMENTS IS GIVEN
      IN THE FIRST TWO EXAMPLES OF THIS SECTION.
END
```

TIME = 0



ENTER COMMAND

STEPHENSON'S KINEMATIC CHAIN

FIG. 9.10

9.5 UNDAMPED FREE VIBRATION [TWO DEGREE OF FREEDOM]
(REFER TO EXAMPLE 7.7 OF CHAPER 7.)

```
LIST

PART/1,GROUND
MARKER/10,GMARKER,PART=1,X=0,Y=0,ANGLE=0
MARKER/21,GMARKER,PART=1,X=0,Y=-3.0,ANGLE=-90
MARKER/51,GMARKER,PART=1,X=0,Y=-6.0,ANGLE=-90

PART/2,MASS=50,CM=30,INERTIA=0.0,ANGLE=0
MARKER/20,GMARKER,PART=2,X=0,Y=0,ANGLE=-90
MARKER/30,POINT,PART=2,X=0,Y=-0.05
MARKER/40,POINT,PART=2,X=0,Y=-0.1

PART/3,MASS=50,CM=60,INERTIA=0.0,ANGLE=0
MARKER/50,GMARKER,PART=3,X=0,Y=0,ANGLE=-90
MARKER/60,POINT,PART=3,X=0,Y=-0.05
MARKER/70,POINT,PART=3,X=0,Y=-0.1

TRANSLATION/1,I=20,J=21,TRANS=0,DTRANS=25
TRANSLATION/2,I=50,J=51,TRANS=0,DTRANS=25

FIELD/1,TRANSLATIONAL,SPRING,I=10,J=20,PAR=20,3
FIELD/2,TRANSLATIONAL,SPRING,I=40,J=50,PAR=15,3

SYSTEM/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUTPUT/END=0.015,STEPS=20,SAVEINT,GRSAVE,NOPLOT

REQUEST/1,DISPLACEMENT,I=20,J=10
REQUEST/2,DISPLACEMENT,I=50,J=10

REQUEST/3,VELOCITY,I=20,J=10
REQUEST/4.VELOCITY,I=50,J=10

REQUEST/5,ACCELERATION,I=20,J=10
REQUEST/6,ACCELERATION,I=50,J=10

                        GRAPHICS

GRAPHICS/100,CIRCLE,CM=10,RADIUS=0.2
GRAPHICS/200,SP,I=10,J=20,N=4,DA=1,LA=0.1,LB=0.1
     SP==> THE SPRING WHICH IS ATTACHED BETWEEN TWO MARKERS I=10 &
     J=20. N==> NUMBER OF COILS TO BE DRAWN IN THE SPRING.
     DA==> OUTER DIAMETER OF THE SPRING IN INCHES.
     LA==> DISTANCE BETWEEN MARKER 10 AND THE FIRST COIL OF THE
     SPRING. LB==> DISTANCE BETWEEN MARKER 20 AND THE LAST COIL
     OF THE SPRING.
GRAPHICS/300,CIRCLE,CM=20,RADIUS=0.2
GRAPHICS/400,CIRCLE,CM=40,RADIUS=0.2
GRAPHICS/500,OUTLINE=20/40

GRAPHICS/600,SP,I=40,J=50,N=4,DA=1,LA=0.1,LB=0.1
     SP==> THE SPRING WHICH IS ATTACHED BETWEEN TWO MARKERS I=40 &
     J=50. N==> NUMBER OF COILS TO BE DRAWN IN THE SPRING.
     DA==> OUTER DIAMETER OF THE SPRING IN INCHES.
     LA==> DISTANCE BETWEEN MARKER 40 AND THE FIRST COIL OF THE
     SPRING. LB==> DISTANCE BETWEEN MARKER 50 AND THE LAST COIL
     OF THE SPRING.
GRAPHICS/700,CIRCLE,CM=50,RADIUS=0.2
```

```
GRAPHICS/800,CIRCLE,CM=70,RADIUS=0.2
GRAPHICS/900,OUTLINE=50/70
```

*** NOTE ***

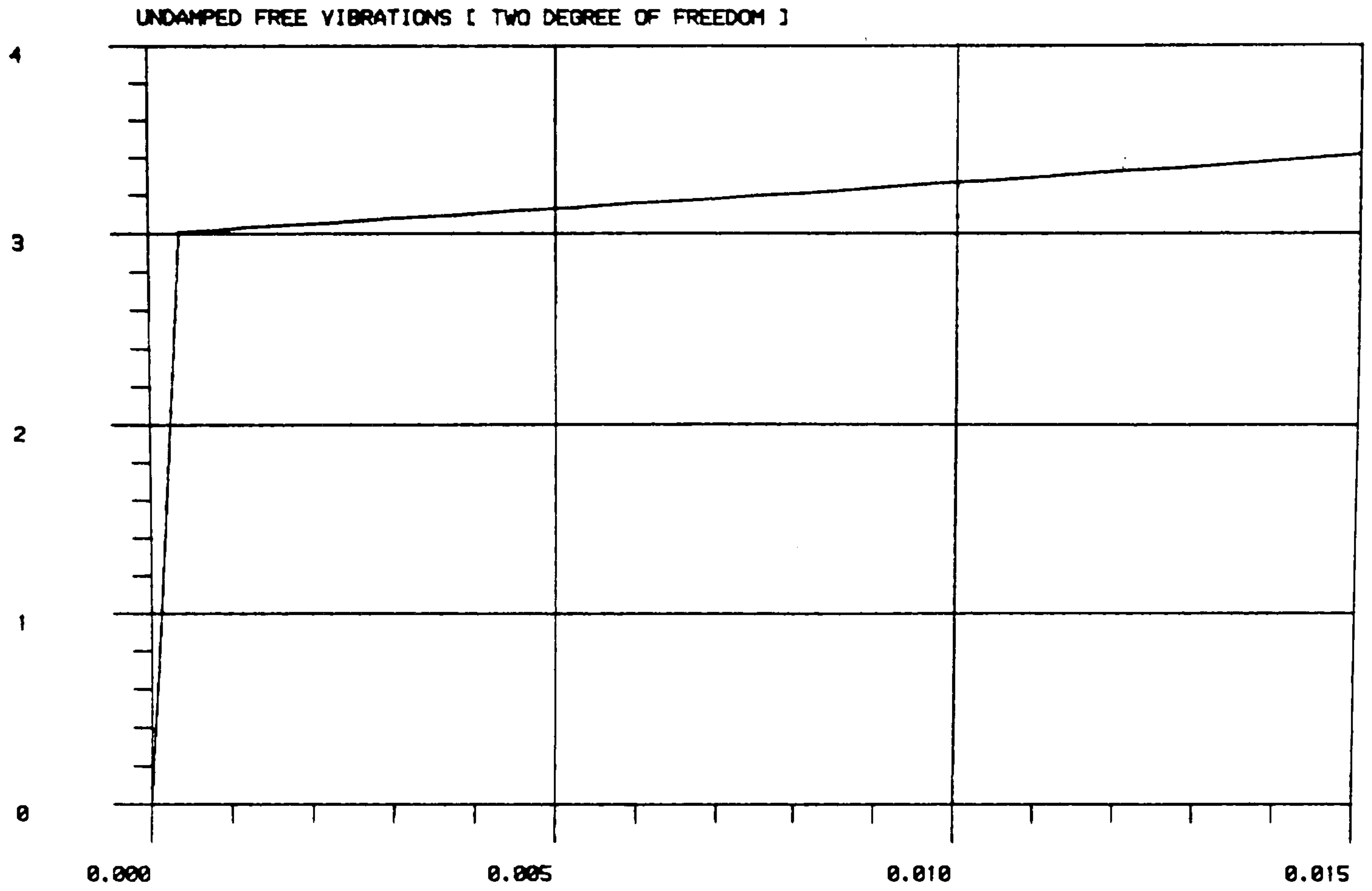
THE DESCRIPTION OF ALL OTHER GRAPHICS STATEMENTS IS GIVEN IN THE FIRST TWO EXAMPLES OF THIS SECTION.

END


TIME = 0
ENTER COMMAND
UNDAMPED FREE VIBRATIONS [TWO DEGREE OF FREEDOM]

FIG. 9.11

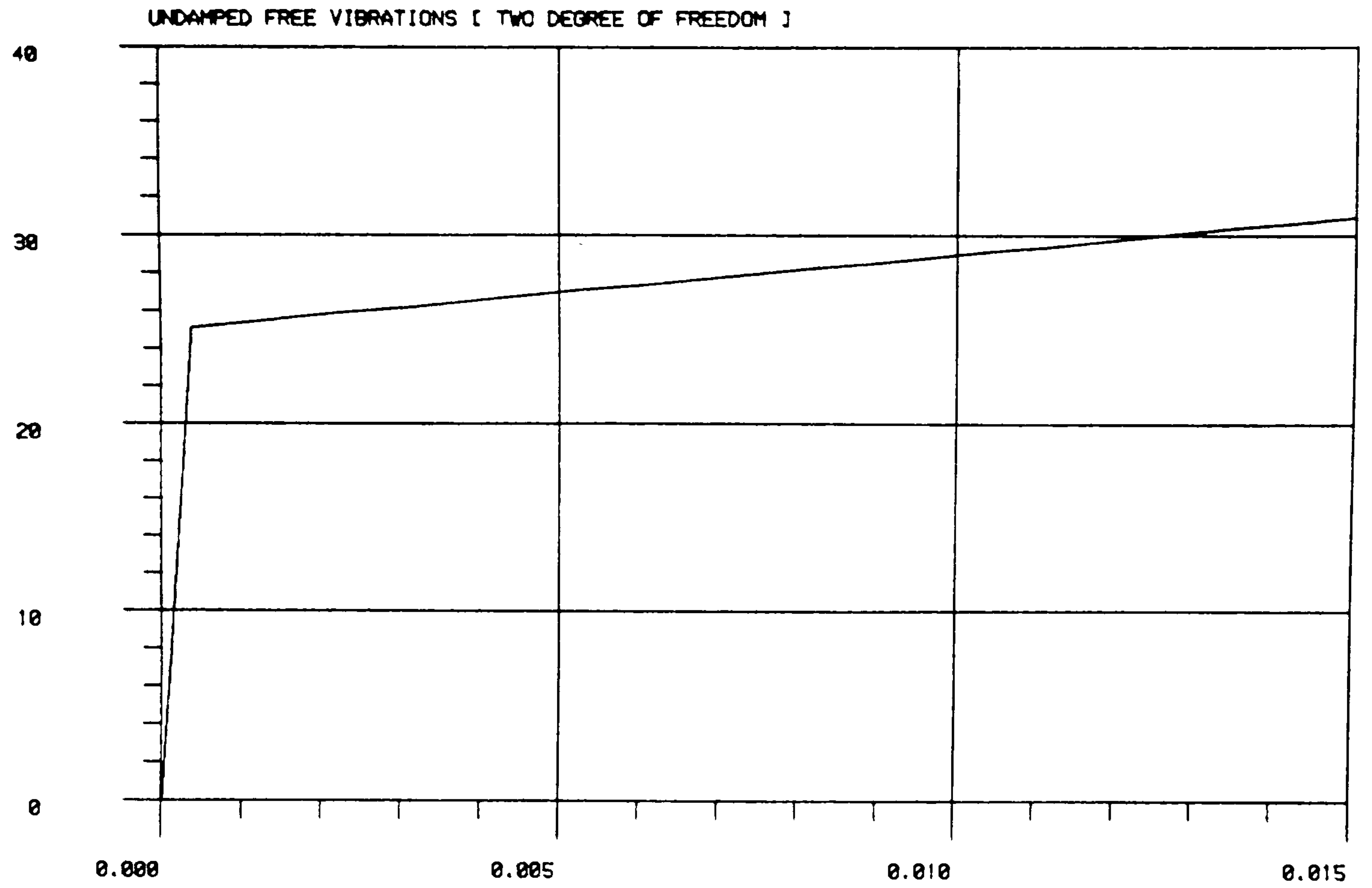
ENTER COMMAND




```
PLOT             X AXIS                        Y AXIS
 NO  REQ#  COMP  TYPE    I     J    REQ#  COMP  TYPE    I     J   RUN  FILE
  1              TIME                  1  MAG   DISP   20    10    1    12
```

FIG. 9.12 : DIPLACEMENT OF MASS 1.

ENTER COMMAND




```
PLOT            X AXIS                          Y AXIS
 NO REQ# COMP TYPE    I     J    REQ# COMP TYPE    I     J  RUN FILE
  1            TIME                  4 MAG  VEL    50    10  1   12
```

FIG. 9.13 : VELOCITY OF MASS 2.

9.6 TOGGLE MECHANISM

(REFER TO EXAMPLE 7.9 OF CHAPTER 7.)

```
PA/1,GR
MA/17,GM,PA=1,X=0,Y=0,AN=0
MA/1,GM,PA=1,X=-6.0,Y=-4,AN=0
MA/12,PO,PA=1,X=0,Y=-7.1677097,AN=-90

PA/2,MA,CM=3,IN,AN=-135
PA/2,DE=-180.0
MA/2,GM,PA=2,X=0,Y=0,AN=0
MA/3,PO,PA=2,X=0.5,Y=0
MA/4,PO,PA=2,X=1.0,Y=0

PA/3,MA,CM=6,IN,AN=14
MA/5,GM,PA=3,X=0,Y=0,AN=0
MA/6,PO,PA=3,X=2.5,Y=0
MA/7,PO,PA=3,X=5.0,Y=0

PA/4,MA,CM=16,IN,AN=62
MA/14,GM,PA=4,X=0,Y=0,AN=0
MA/15,PO,PA=4,X=2.0,Y=0
MA/16,PO,PA=4,X=4.0,Y=0,Y=0

PA/5,MA,CM=9,IN,AN=112
MA/10,GM,PA=5,X=0,Y=0,AN=0
MA/9,PO,PA=5,X=2.5,Y=0
MA/8,GM,PA=5,X=5.0,Y=0,AN=0

PA/6,MA,CM=11,IN,AN=0
MA/11,GM,PA=6,X=0,Y=0,AN=-90

RO/1,1,2
RO/2,4,5
RO/3,7,8
RO/4,8,14
RO/5,10,11
RO/6,17,16

TR/1,11,12,TRANS=1


GE/1,RO,ON=2,CO,DE=-180.0,PAR=-135.0D

SY/GC=386.088,JGRAV=-386.088,ERR=1.E-4,IC

OUT/END=2,STEPS=20,NOPLOT,SAVEINT,GRSAVE

REQ/1,DIS,11,12

REQ/2,VEL,11,12

REQ/3,ACC,11,12
```

GRAPHICS

```
GR/101,CI,CM=17,RA=0.2,SEG=4
GR/102,CI,CM=1,RA=0.2,SEG=4
GR/103,CI,CM=12,RA=0.2,SEG=4
```

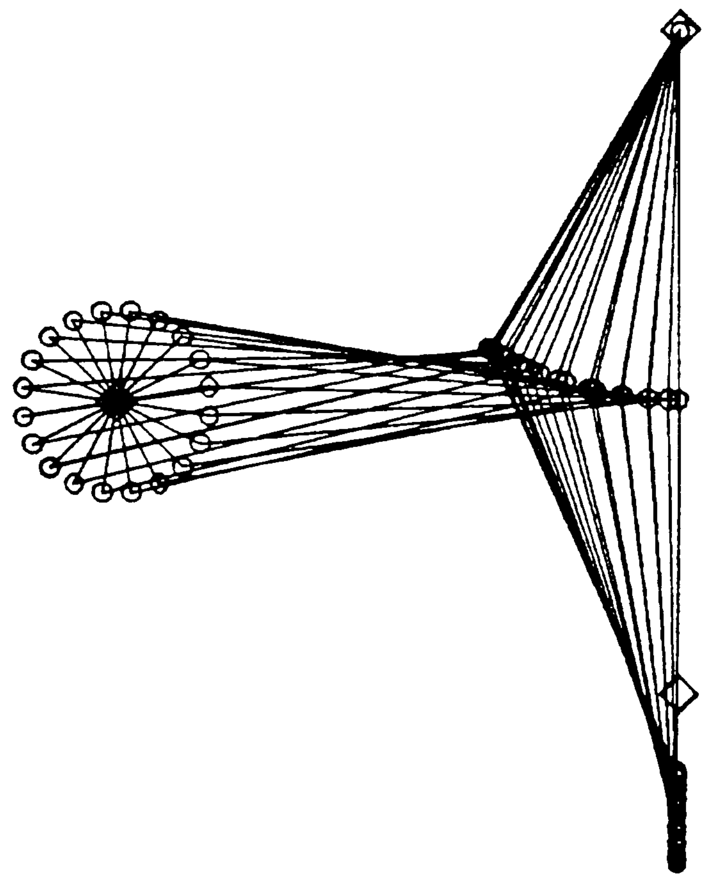
```
GR/104,CI,CM=2,RA=0.1
GR/105,CI,CM=4,RA=0.1
GR/106,OUT=2,4

GR/107,CI,CM=5,RA=0.1
GR/108,CI,CM=7,RA=0.1
GR/109,OUT=5,7

GR/110,CI,CM=14,RA=0.1
GR/111,CI,CM=16,RA=0.1
GR/112,OUT=14,16

GR/113,CI,CM=8,RA=0.1
GR/114,CI,CM=10,RA=0.1
GR/115,CI,CM=11,RA=0.1,SEG=4
GR/116,OUT=8,10
```

ABBREVIATIONS

```
GR==>  GRAPHICS
CI==>  CIRCLE
RA==>  RADIUS
OUT==> OUTLINE
```

END

TIME = 0



ENTER COMMAND

TOGGLE MECHANISM

FIG. 9.14

CHAPTER 10 : MISCELLANEOUS USER INFORMATION

10.1 IMPORTANT NOTES

1. The ground reference axis (frame) system must be as shown in the figure 10.1 for any type of problem. The gravitational force acts in the negative direction of the Y axis, hence the value of JGRAV in the SYSTEM statement must be negative.

FIG.10.1 : GROUND REFERENCE AXIS

2. The example can be solved either in the FPS system or in the SI system by changing the values of the gravitational constant and JGRAV in the respective unit system. It is important to remember that units of the gravitational constant and JGRAV must be consistent with the units of input data statements. See section 10.2 .
3. The values of the mass and mass moment of inertia must be consistent with the gravitational constant. DRAM will automatically divide these values by the gravitational constant. For more details refer to section 10.2.
4. The values of mass and mass moment of inertia need not be supplied if only the displacement, velocity and acceleration of a kinematic system are required. However, for a force analysis these values must be supplied. Otherwise, the calculated values of force will not be accurate.

5. Sometimes DRAM displays the following error message while running DRAM.

"LOOP CLOSER FAILED AFTER 25 ITERATIONS SUBROUTINE ERROR CALLED".

The Error is due to improper geometry of the mechanical system. That is, lengths and respective angles of the mechanical system are not as accurate as DRAM needs to close the loop. The corrective action will be to consider the maximum number of digits after a decimal point in order to input the geometry (angles and lengths) of the mechanical system.

6. The following error will occasionally occur.

"---- WARNING (ICHECK): GENERATOR - IC CONFLICT ON PART 4 GENERATOR 1 TAKES PRECEDENCE ON PART 4 "

DRAM displays this message because the specified angular velocity in PART 4 statement does not match with the specified angular velocity in GENERATOR 1.

7. Title for the RSUB subroutine output results:

As the RSUB subroutine prints three output results in columns one after another, the titles of three different results must be abbreviated due small space provided by DRAM. Only 48 alphanumeric characters are allowed for the title.

8. While running DRAM GRAPHICS if any link of the mechanism slips off from its rotational point or joint, then the assigned value of ERR must be lowered (from 0.1E-04 to still lower number).

9. One of the displayed messages on the screen is:
"DO YOU HAVE YOUR OWN LINKED VERSION OF DRAM ?"
The answer to this question is YES if the program is needed to run a second time without making any change in the subprogram. This saves linking time of the subprogram to DRAM.

10. "ENTER COMMAND FILE NAME"
This message is displayed while running DRAM GRAPHICS. However, if it is not necessary to use this command for the graphics, just hit the carriage return.

11. After finishing this manual, it important to read Mechanical Dynamic Inc's user guide for some information which may not have been covered in this manual.

10.2 UNIT TABLE

Comments about the system of units :

All computer codes developed at MDI have been designed to accept any consistent homogeneous set of units. There does exist a wide varity of units that the user may choose from, some of which regrettably lead to a rather bewildering set of units.

A list of some of the more common and more scientific units is assembled here to prevent confusion that could possibly occur while inputting data to the program.

Table 10.2 - UNIT TABLE *

SYS	LGTH	M	ACCEL	F	Gc	G(-JGRAV)	INTERIA
SI	M	KG	M/S2	N	1.0	9.81M/S2	KG-M2
METRIC	MM	KG	MM/S2	N	1000.0	9807MM/S2	KG-MM2
METRIC	MM	G	MM/S2	N	1.0E+6	9807MM/S2	G-MM2
METRIC	M	KG	M/S2	KGF	9.81	9.81M/S2	KG-M2
METRIC	CM	KG	CM/S2	KGF	981	981CM/S2	KG-CM2
FPS	FT	SLUG	FT/S2	LBF	1.0	32.2FT/S2	S/NG-FT2
FPS	FT	LBM	FT/S2	LBF	32.2	32.2FT/S2	LBM-FT2
	IN	LBM	IN/S2	LBF	386.2	386.2IN/S2	LBM-IN2

NOTE: S2 = S**2, TIME UNIT IS SECONDS.

* MDI-Mechnical Dynamics, Inc.

APPENDIX A : ANALYTICAL SOLUTIONS OF EXAMPLE PROBLEMS WITH COMPARISONS OF RESULTS TO DRAM

EXAMPLE # A.1 Slender rod:-

Given:

Weight $W = 40$ lbf

mass $m = \frac{40}{386.088} = 1.3685894$ lbf sec sq/ft

Length of Slender rod $= 4.9166667$ ft.

Mass moment of inertia

$= 11.010755$ lbf ft sec^2

Initial Condition:-

$\theta = 45^\circ$ at $t = 0$

$\dot{\theta} = 0$ rad/sec at $= 0$

Find: Determine the angular displacement and velocity of the given sytem.

Diagram:-

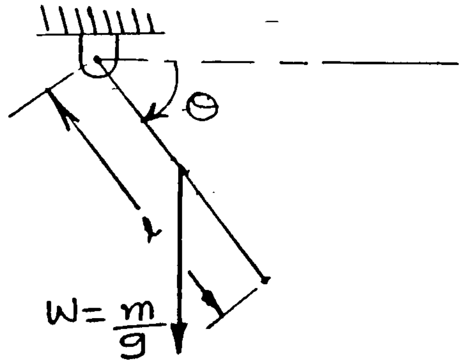


FIG. A1: Slender Rod.

Motion equation for linear system:-

For motion of system with the amplitude θ, the kinetic energy can be written as follows

Kinetic Energy $(T) = \frac{1}{2}\left(\frac{1}{12}ml^2\right)\dot{\theta}^2$

Also we can write the potential energy resulting from the gravity force as

Potential Energy $(U) = \frac{1}{2} mgl(1-\cos\theta)$

The total energy of the system can ibe written as

$$K.E + P.E$$

$$= \frac{1}{2}\left(\frac{1}{12}ml^2\right)\dot{\theta}^2 + 1/2\, mgl(1-\cos\theta)$$

For a Conservative system:

$$\frac{\partial (K.E + P.E)}{\partial t} = 0$$

So $$\frac{1}{2}\left(\frac{1}{12}ml^2\right)2\dot{\theta}\ddot{\theta} + 1/2\, mgl(\sin\theta)\dot{\theta} = 0$$

$$\frac{l}{6}\ddot{\theta} + g\sin\theta = 0$$

OR $$\ddot{\theta} + \frac{6g}{l}\sin\theta = 0$$

OR $$\ddot{\theta} + \frac{6g}{l}\theta = 0$$ For θ small $\sin\theta \simeq \theta$

So. $$W_n = \sqrt{\frac{6g}{l}}$$

The general solution of the obtained differential equation will be

$$\theta = A\cos\omega t + B\sin\omega t$$

where A, B are the constants whose values can be calculated by imposing initial conditions. Let us impose initial conditions as follows:

At $t=0$, $\theta=\theta_0$

$$\theta_0 = A\cos(0) + 0$$

$$\therefore A = \theta_0$$

At $t=0$, $\dot{\theta}=\dot{\theta}_0$

$$\dot{\theta} = -A\omega \sin\omega t + B\omega\cos\omega t$$

$$\therefore \quad \dot{\theta}_0 = -\theta_0\omega\,(0) + B\omega\,(1)$$

$$\therefore \quad B = \dot{\theta}_0/\omega$$

By substituting the calculated values of A & B we get

$$\theta = \theta_0\cos\omega t + (\dot{\theta}_0/\omega)\sin\omega t \implies \text{Angular displacement}$$

$$\dot{\theta} = -\theta_0\omega\sin\omega t + \left(\frac{\dot{\theta}_0}{\omega}\right)\omega\sin\omega t$$

$$= -\theta_0\omega\sin\omega t + \dot{\theta}_0\sin\omega t \implies \text{Angular velocity.}$$

Analytical Solution:-

The natural frequency of oscillation

$$\omega_n = \sqrt{\frac{6\times g}{l}} = \sqrt{\frac{6\times 32.2}{4.9166667}}$$

$$= 6.26685656 \text{ rad/sec}$$

Angular displacement:-

$$\theta_0 = 360 - 45 = 315 \quad \text{(measured ccw direction)}$$

$$\therefore \theta = \theta_0 \cos \omega t$$

At $t = 0.05$ sec

Note:- A small time interval has been chosen so that it will be possible to compare the analytical linear solution with the non linear solution obtained by the DRAM.

$$\therefore \theta = 315 \cos(6.26685656 \times 0.05)$$

$$= 314.99529^{\circ}$$

Angular velocity:-

$$\dot{\theta} = -\theta_0 \omega \sin \omega t + \dot{\theta}_0 \sin \omega t$$

at $t = 0.05$

$$\dot{\theta} = -315(6.26685656) \sin(6.26685656 \times 0.05)$$

$$= 10.795813 \text{ rad/sec}$$

As DRAM gives a non linear solution to this proulbem, the linear analytical solution has been compared with DRAM results in the following result chart:

	ANALYTICAL RESULTS A_N	DRAM RESULTS D_R	% DEVIATION $\left\lvert\frac{A_N - D_R}{A_N}\right\rvert 100$
AT TIME T=0.05 SEC.			
Angular displacement in degrees	314.99529	314.715	0.0889
Angular velocity rad/sec	10.795813	*11.690076	8.2834

Table No. 1: Comparison of Analytical Results with DRAM Results

NOTE. DRAM results are only comparable at a very small time interval.

* DRAM results are multiplyed by 12 Since all input values are in Feet.

EXAMPLE # A.2 Slider Crank Mechanism
(Applied force externally)

Given:–

Lengths:–

$\bar{r}_2 = 0.16666667$ ft, $\bar{r}_3 = 0.66666667$ ft.

$\bar{b} = 0.02522921$ ft, $\bar{X} = 0.68346737$ ft.

$m_2 = 0.00776398$ lbf sec^2/ft

$m_3 = 0.0310554$ lbf sec^2/ft

$m_4 = 0.04658385$ lbf sec^2/ft.

$I_2 = 0.00001797$ lbf ft. sec^2

$I_3 = 0.00115021$ lbf ft. sec^2

$I_4 = 0.00000674$ lbf ft. sec^2

Initial Conditions:–

$\theta_2 = 30^\circ$ when $t = 0$

$\theta_3 = -5^\circ$ when $t = 0$

$\dot{\theta}_2 = 3000$ rpm. CCW) $\Longrightarrow$ Constant.

$\alpha_2 = 0$

Find:– Determine the velocity, acceleration and force (exerted by slider on link 3)

Diagram:–

Applied Force

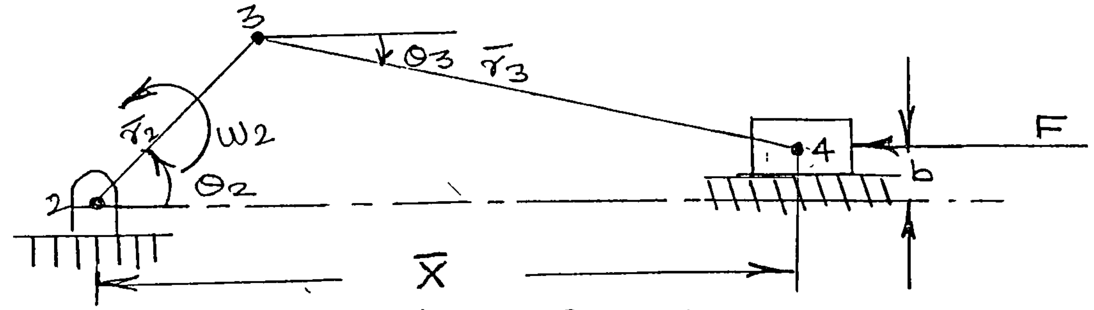


FIG. A.2 : Slider Crank

Theory:-

The solution to this prombem is given by using the complex variable method In this method, it is essential to write the position equation. It is accomplished by writing the position vector. i.e.

Position vector:-

$$\bar{r}_2 + \bar{r}_3 = \bar{x} + i\bar{b}$$

or $$\bar{r}_2 e^{i\theta_2} + \bar{r}_3 e^{i\theta_3} = \bar{x} + i\bar{b}$$

$$\bar{r}_2(\cos\theta_2 + i\sin\theta_2) + \bar{r}_3(\cos\theta_3 + i\sin\theta_3) = \bar{x} + i\bar{b}$$

$$\because e^{i\theta} = \cos\theta + i\sin\theta$$

Let us separate real & imaginary parts.

$$\bar{r}_2 \cos\theta_2 + \bar{r}_3 \cos\theta_3 = \bar{x} \implies \text{Real}$$

$$\bar{r}_2 \sin\theta_2 + \bar{r}_3 \sin\theta_3 = b \implies \text{imaginary}.$$

By differentiating these two equation, the angular velocity can be calulated.

$$\bar{r}_2(-\sin\theta_2)\dot{\theta}_2 + \bar{r}_3(-\sin\theta_3)\dot{\theta}_3 = \dot{x} \quad \text{———(1)}$$

$$\bar{r}_2(\cos\theta_2)\dot{\theta}_2 + \bar{r}_3(\cos\theta_3)\dot{\theta}_3 = 0 \quad \text{———(2)}$$

The angular acceleration can be calculated by differentiating the equation (1) & (2) again

So.

$$\bar{r}_2(-\cos\theta_2)(\dot{\theta}_2)^2+\bar{r}_2(-\sin\theta_2)\ddot{\theta}_2$$
$$+\bar{r}_3(-\cos\theta_3)(\dot{\theta}_3)^2-\bar{r}_3\sin\theta_3\ddot{\theta}_3=\ddot{x} \qquad \text{——— (3)}$$

&

$$\bar{r}_2(-\sin\theta_2)(\dot{\theta}_2)^2+\bar{r}_2\cos\theta_2\ddot{\theta}_2$$
$$+\bar{r}_3(-\sin\theta_3)(\dot{\theta}_3)^2+\bar{r}_3(\cos\theta_3)\ddot{\theta}_3=0 \qquad \text{——— (4)}$$

A. analytical solution of slider crank mechanism can simply be obtained by using above derived equations.

Analytical Solution:-

Linear and angular velocities:-

Substitute given values in the equations (1), & (2)

First, equation (2) :

i.e. $\dot{\theta}_3=-\dot{\theta}_2\dfrac{r_2}{r_3}\left(\dfrac{\cos\theta_2}{\cos\theta_3}\right)$

$$=-314.15\ \frac{0.16666667}{0.66666667}\left(\frac{\cos 30^\circ}{\cos 355^\circ}\right)$$

$$\dot{\theta}_3=-68.275278 \text{ rad/sec (CW)}$$

Second, equation (1):

$$\bar{r}_2(-\sin\theta_2)\dot{\theta}_2+\bar{r}_3(-\sin\theta_3)\dot{\theta}_3=\dot{x}$$

$$(0.16666667)(-\sin 30^\circ)(314.15)+(0.66666667)(\sin 355^\circ)(-68.275278)$$
$$=\dot{x}$$

$$\therefore\ \dot{x}=-30.14622 \text{ ft/sec.}$$

Linear and angular accelerations:-

Substitue the given values and calculated values in the equations (3) & (4)

First equation (4):

$$\ddot{\theta}_3 = \frac{\bar{r}_2 \sin\theta_2(\dot{\theta}_2)^2 + \bar{r}_3 \sin\theta_3(\dot{\theta}_3)^2}{\bar{r}_3 \cos\theta_3}$$

$\because \ddot{\theta}_2 = 0$

$\omega_2 \Rightarrow$ const.

$$= \frac{0.16666667 \sin 30^0 (314.15)^2 + 0.66666667 \sin 355^0 (-68.275278)^2}{0.66666667 \cos 355^0}$$

$$\ddot{\theta}_3 = 11975.571 \text{ rad/sec}^2$$

2nd equation (3):

$$\ddot{x} = \bar{r}_2(-\cos\theta_2)\dot{\theta}_2^2 + \bar{r}_3(-\cos\theta_3)(\dot{\theta}_3)^2 + \bar{r}_3 \sin\theta_3 \ddot{\theta}_3$$

$$= 0.16666667(-\cos 30^0)(314.15)^2 + 0.66666667(-\cos 355^0) \times (-68.275278)^2 - 0.16666667(\sin 355^0)(11975.571)$$

$$\ddot{x} = -16644.76 \text{ ft/sec}^2$$

Force Analysis:-

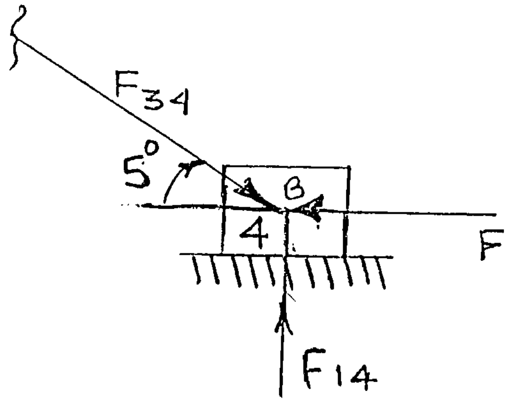


FIG. A 2.1 : Slider (Free body diagram)

By Newton's law:-

$$\Sigma F = ma$$

$$\xrightarrow{+} \Sigma F_x = ma$$

$$F_{34} \cos 5^0 - F = ma$$

$$F_{34} \cos 5^0 - 11.024845 = 0.04658385 \times 16644.73$$

$$F_{34} = \frac{775.37561 - 11.024845}{\cos 5^0}$$

$$= 767.27046 \text{ lbf}$$

RESULT CHART ⟶

	ANALYTICAL RESULTS A_N	DRAM RESULTS D_R	PERCENTAGE DEVIATION $\left\lvert \frac{A_N - D_R}{A_N} \right\rvert 100$
Angular Velocity ($\dot{\theta}_3$) rad/sec	-68.275278	-68.277294	0.0029
Velocity ($\dot{X}$) Ft./sec	-30.14622	-30.1413181	0.016
Angular Acceleration ($\ddot{\theta}_3$) rad/sec^2	11975.571	11976.3	0.0060
Acceleration ($\ddot{X}$) Ft./sec	-16644.76	-16645.7	0.0056
Force (F_{43}) lbf	767.27046	775.452	1.1

Table NO. 2: Comparison of Analytical Results with DRAM Results And % deviation.

EXAMPLE # A.3 Sixbar linkage Mechanism:

Given:- Distances:-

$\bar{r}_1 = 2.9965472$ inches, $\bar{r}_2 = 1$ inch,

$\bar{r}_3 = 2$ inches, $\bar{r}_4 = 2$ inches, $\bar{r}_5 = 2.5$ inches

$\bar{r}_6 = 2.6$ inches.

Angles:-

$\theta_2 = 45^\circ$, $\theta_3 = 35^\circ$, $\theta_4 = 109^\circ$,

$\theta_5 = 59^\circ$, $\theta_6 = 87^\circ$

Velocities:-

$\omega_2 = 4000$ rpm (constant)

Accelerations:-

$\alpha_2 = 0$

Since no Force analysis is required, the masses are not specified.

Find:- Determine the displacement, velocity and acceleration of the Sixbar linkage mechanism.

Diagram:

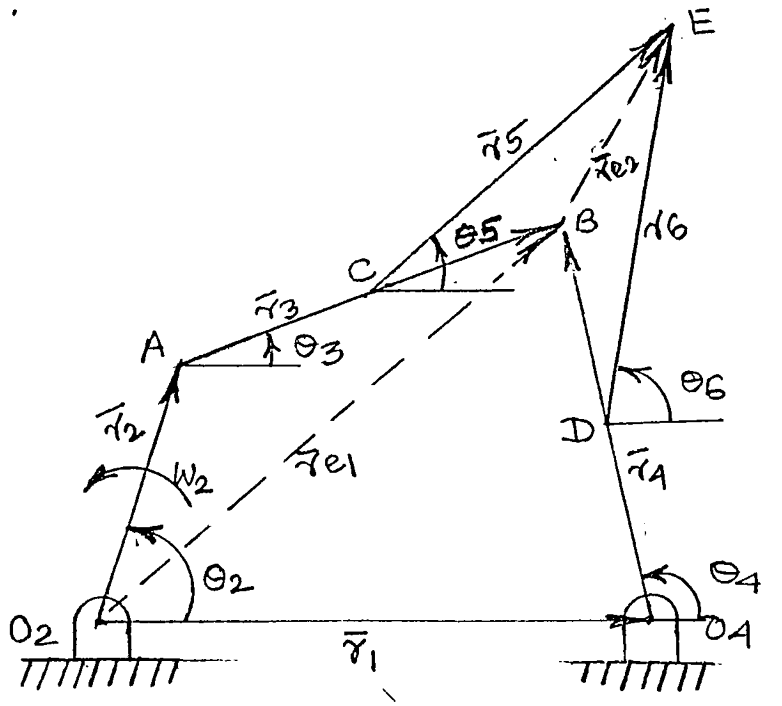


FIG. A 3 : Six-bar linkage mechanism.

Theory:-

There are various methods to solve the six-bar linkage mechanism. The complex variable method is used in this analytical solution.

In the complex variable method, the position equation for the six-bar linkage kinematic mechanism can be written as.

$$\bar{r}e_1 = \bar{r}_2 + \bar{r}_3 = \bar{r}_1 + \bar{r}_4 \qquad \text{------ (1)}$$
$$\bar{r}e_2 = \bar{r}_5 - \tfrac{1}{2}\bar{r}_3 = \bar{r}_6 - \tfrac{1}{2}\bar{r}_4 \qquad \text{------ (2)}$$

Equation (1) describes a 4-bar linkage while the equation (2) describes 6-bar linkage. Before getting into the 6-bar mechanism, it is necessary to consider the 4-bar linkage: First, by solving the equation (1):

$$\bar{r}_2 e^{i\theta_2} + \bar{r}_3 e^{i\theta_3} = \bar{r}_1 e^{i\theta_1} + \bar{r}_4 e^{i\theta_4}$$
$$\bar{r}_2 e^{i\theta_2} + \bar{r}_3 e^{i\theta_3} = \bar{r}_1 + r_4 e^{i\theta_4} \qquad \because \theta_1 = 0$$

Now $e^{i\theta} = \cos\theta + i\sin\theta$, so

$$\bar{r}_2[\cos\theta_2 + i\sin\theta_2] + \bar{r}_3[\cos\theta_3 + i\sin\theta_3] = \bar{r}_1 + \bar{r}_4[\cos\theta_4 + i\sin\theta_4]$$

Let us separate real and imaginary parts

$$\bar{r}_2\cos\theta_2 + \bar{r}_3\cos\theta_3 = \bar{r}_1 + \bar{r}_4\cos\theta_4 \implies \text{Real Part}$$
$$\bar{r}_2\sin\theta_2 + \bar{r}_3\sin\theta_3 = +\bar{r}_4\sin\theta_4 \implies \text{Imaginary part.}$$

The angular velocity can be calculated by differentiating the above two equations. Therefore

$$\bar{r}_2\dot{\theta}_2(-\sin\theta_2) + \bar{r}_3\dot{\theta}_3(-\sin\theta_3) = 0 + \bar{r}_4\dot{\theta}_4(-\sin\theta_4) \qquad \text{--- (3)}$$
$$\bar{r}_2\dot{\theta}_2(\cos\theta_2) + \bar{r}_3\dot{\theta}_3(\cos\theta_3) = +\bar{r}_4\dot{\theta}_4(\cos\theta_4) \qquad \text{--- (4)}$$

Further, these two equations must be differentiated to find the angular accelerations which can be done as

$$\bar{r}_2(\dot{\theta}_2)^2(-\cos\theta_2) + \bar{r}_2\ddot{\theta}_2(-\sin\theta_2) + \bar{r}_3(\dot{\theta}_3)^2(-\cos\theta_3)$$
$$+ \bar{r}_3\ddot{\theta}_3(-\sin\theta_3) = \bar{r}_4(\dot{\theta}_4)^2(-\cos\theta_4) + \bar{r}_4\ddot{\theta}_4(-\sin\theta_4) \qquad \text{---- (5)}$$

$$\bar{r}_2(\dot{\theta}_2)^2(-\sin\theta_2)+\bar{r}_2\ddot{\theta}_2\cos\theta_2+\bar{r}_3(\dot{\theta}_3)^2(-\sin\theta_3)+\bar{r}_3\ddot{\theta}_3(\cos\theta_3)$$
$$=\bar{r}_4(\dot{\theta}_4)^2(-\sin\theta_4)+\bar{r}_4\ddot{\theta}_4(\cos\theta_4) \quad ------ (6)$$

All values of accelerations, velocities and displacements of the four bar linkage mechanism need to be calculated by using the equations from (3) to (6)

Let us solve the equation(2) for six-bar linkage i.e.

$$\bar{r}_{e2}=\bar{r}_5-\tfrac{1}{2}\bar{r}_3=\bar{r}_6-\tfrac{1}{2}\bar{r}_4$$
$$\bar{r}_5 e^{i\theta_5}-\tfrac{1}{2}\bar{r}_3 e^{i\theta_3}=\bar{r}_6 e^{i\theta_6}-\tfrac{1}{2}\bar{r}_4 e^{i\theta_4}$$
$$\bar{r}_5(\cos\theta_5+i\sin\theta_5)-\tfrac{1}{2}\bar{r}_3(\cos\theta_3+i\sin\theta_3)$$
$$=\bar{r}_6(\cos\theta_6+i\sin\theta_6)-\tfrac{1}{2}\bar{r}_4(\cos\theta_4+i\sin\theta_4)$$
$$\because e^{i\theta}=\cos\theta+i\sin\theta$$

Let us separate real and imaginary parts

$$\bar{r}_5\cos\theta_5-\tfrac{1}{2}\bar{r}_3\cos\theta_3=\bar{r}_6\cos\theta_6-\tfrac{1}{2}\bar{r}_4\cos\theta_4 \Longrightarrow \text{Real}$$
$$\bar{r}_5\sin\theta_5-\tfrac{1}{2}\bar{r}_3\sin\theta_3=\bar{r}_6\sin\theta_6-\tfrac{1}{2}\bar{r}_4\sin\theta_4 \Longrightarrow \text{Imaginary}$$

Differentiate these two equations in order to calculate the angular velocities, so:

$$\bar{r}_5(\dot{\theta}_5)(-\sin\theta_5)-\tfrac{1}{2}\bar{r}_3(\dot{\theta}_3)(-\sin\theta_3)$$
$$=\bar{r}_6(\dot{\theta}_6)(-\sin\theta_6)-\tfrac{1}{4}\bar{r}_4(\dot{\theta}_4)(-\sin\theta_4) \quad ---(7)$$
$$\bar{r}_5(\dot{\theta}_5)(\cos\theta_5)-\tfrac{1}{2}\bar{r}_3(\dot{\theta}_3)\cos\theta_3$$
$$=\bar{r}_6(\dot{\theta}_6)\cos\theta_6-\tfrac{1}{2}\bar{r}_4(\dot{\theta}_4)\cos\theta_4 \quad ---(8)$$

Now, Differentiate these two equations again in order to calculate angular accelerations. Therefore,

$$\bar{r}_5(\dot{\theta}_5)^2(-\cos\theta_5)+\bar{r}_5(\ddot{\theta}_5)(-\sin\theta_5)-\tfrac{1}{2}\bar{r}_3(\dot{\theta}_3)^2(-\cos\theta_3)$$
$$-\tfrac{1}{2}\bar{r}_3(\ddot{\theta}_3)(-\sin\theta_3)=\bar{r}_6(\dot{\theta}_6)^2(-\cos\theta_6)+\bar{r}_6(\ddot{\theta}_6)(-\sin\theta_6)$$
$$-\tfrac{1}{2}\bar{r}_4(\dot{\theta}_4)^2(-\cos\theta_4)-\tfrac{1}{2}\bar{r}_4(\ddot{\theta}_4)(-\sin\theta_4) \quad \text{-----} (9)$$

$$\bar{r}_5(\dot{\theta}_5)^2(-\sin\theta_5)+\bar{r}_5(\ddot{\theta}_5)(\cos\theta_5)-\tfrac{1}{2}\bar{r}_3(\dot{\theta}_3)^2(-\sin\theta_3)$$
$$-\tfrac{1}{2}\bar{r}_3(\ddot{\theta}_3)\cos\theta_3=\bar{r}_6(\dot{\theta}_6)^2(-\sin\theta_6)+\bar{r}_6(\ddot{\theta}_6)\cos\theta_6$$
$$-\tfrac{1}{2}\bar{r}_4(\dot{\theta}_4)^2(-\sin\theta_4)-\tfrac{1}{2}\bar{r}_4(\ddot{\theta}_4)(\cos\theta_4) \quad \text{------} (10)$$

Analytical solution:-

Four-bar linkage:-

Substitute the values of $\bar{r}_2, \bar{r}_3, \bar{r}_4, \dot{\theta}_2, \theta_2, \theta_3 \theta_4$ into the equations (3) and (4), we will have

$$1\times 418.879(-\sin 45^\circ)+2\times\dot{\theta}_3(-\sin 35^\circ)=2\times\dot{\theta}_4(-\sin 109^\circ)$$
$$1\times 418.879(\cos 45^\circ)+2\times\dot{\theta}_3(\cos 35^\circ)=2\times\dot{\theta}_4(\cos 109^\circ)$$

$$-296.192+1.1471\,\dot{\theta}_3=-1.8910\,\dot{\theta}_4$$
$$296.192+1.6386\,\dot{\theta}_3=-0.6511\,\dot{\theta}_4$$

By rearranging

$$-1.1471\dot{\theta}_3+1.8910\dot{\theta}_4=296.192 \quad \text{——} (A)$$
$$1.6383\,\dot{\theta}_3+0.6511\,\dot{\theta}_4=-296.192 \quad \text{——} (B)$$

Now by Cramer's Rule:-

$$\dot{\theta}_3=\frac{\begin{vmatrix}296.192 & 1.8910\\ -296.192 & 0.6511\end{vmatrix}}{\begin{vmatrix}-1.1471 & 1.8910\\ 1.6383 & 0.6511\end{vmatrix}}=\frac{752.92}{-3.8448}$$

$$=-195 \text{ rad/sec (CW)}$$

$$\dot{\theta}_4 = \frac{\begin{vmatrix} -1.1471 & 296.192 \\ 1.6383 & -296.192 \end{vmatrix}}{\begin{vmatrix} -1.1471 & 1.8910 \\ 1.6383 & 0.6511 \end{vmatrix}} = \frac{-145.4895}{-3.8448}$$

$= 37.84059$ rad/sec (CCW)

Now substulute the respective values (given and Calculated) into the equations (5) & (6) to get the accelerations:

$$1(418.879)^2(-\cos 45^\circ) + 1\times\ddot{\theta}_2(-\sin 45^\circ) + 2\times(-195)^2(-\cos 35^\circ)$$
$$+2\times\ddot{\theta}_3(-\sin 35^\circ) = 2(37.84059)^2(-\cos 109^\circ) + 2\times\ddot{\theta}_4(-\sin 109^\circ)$$

$$1(418.879)^2(-\sin 45^\circ) + 1\times\ddot{\theta}_2 \cos 45 + 2\times(-195)^2(-\sin 35^\circ)$$
$$+2\times\ddot{\theta}_3(\cos 35^\circ) = 2(37.84059)^2(-\sin 109^\circ) + 2\ddot{\theta}_4 \cos 109^\circ$$

By Simplifying:-

$$-124068.68 - 0.7071\cancel{\ddot{\theta}_2}^{\,0} - 62296.513 - 1.1471\ddot{\theta}_3$$
$$= 932.3687 - 1.8910\ddot{\theta}_4 \qquad \because \ddot{\theta}_2 = 0 \Rightarrow \omega_2 - \text{Constant}$$

$$-124068.68 - 0.7071\cancel{\ddot{\theta}_2}^{\,0} - 43620.488 + 1.6383\ddot{\theta}_3$$
$$= -2707.7955 - 0.6511\ddot{\theta}_4 \qquad \because \ddot{\theta}_2 = 0 \Rightarrow \omega_2 - \text{Constant}$$

$$-1.1471\ddot{\theta}_3 + 1.8910\ddot{\theta}_4 = 187297.56 \quad \text{———— (C)}$$
$$1.6383\ddot{\theta}_3 + 0.6511\ddot{\theta}_4 = 164981.37 \quad \text{———— (D)}$$

By Cramer's rule:-

$$\ddot{\theta}_3 = \frac{\begin{vmatrix} 187297.56 & 1.8910 \\ 164981.37 & 0.6511 \end{vmatrix}}{\begin{vmatrix} -1.1471 & 1.8910 \\ 1.6383 & 0.6511 \end{vmatrix}} = \frac{-190030.33}{-3.8449}$$

$= 49423.99$ rad/sec^2 CCW)

$$\ddot{\theta}_4 = \frac{\begin{vmatrix} -1.1471 & 187297.56 \\ 1.6383 & 164981.37 \end{vmatrix}}{\begin{vmatrix} -1.1471 & 1.8910 \\ 1.6383 & 0.6511 \end{vmatrix}} = \frac{-496099.72}{-3.8449}$$

$= 129027.99$ rad/sec^2 (CCW).

Six-bar Linkage:-

All calculated values of the four-bar linkage need to be used to complete the analysis of six-bar linkage. Consider the equations (7) and (8) for the angular velocities.

By substituting respective values in the equations (7) and (8) we get

$$2.5(\dot{\theta}_5)(-\sin 59^\circ) + 2.5(\sin 87^\circ)\,\dot{\theta}_6 = -\tfrac{1}{2}(2)(-195)\sin 35^\circ + \tfrac{1}{2}(2)(37.84059)\sin 109^\circ$$

$$2.5(\dot{\theta}_5)(\cos 59^\circ) - 2.5\dot{\theta}_6\cos 87^\circ = \tfrac{1}{2}(2)(-195)\cos 35^\circ - \tfrac{1}{2}(2)(37.84059)\cos 109^\circ$$

By Simplifying

$$-2.1429\,\dot{\theta}_5 + 2.4965\,\dot{\theta}_6 = 147.6263 \qquad \text{——(E)}$$

$$1.2875\,\dot{\theta}_5 - 0.1308\,\dot{\theta}_6 = -147.416 \qquad \text{——(F)}$$

By Cramer's rule:-

$$\dot{\theta}_5 = \frac{\begin{vmatrix} 147.6263 & 2.4965 \\ -147.415 & -0.1308 \end{vmatrix}}{\begin{vmatrix} -2.1429 & 2.4965 \\ 1.2875 & -0.1308 \end{vmatrix}} = \frac{348.712}{-2.9339}$$

$= -118.854$ rad/sec (CCW)

$$\dot{\theta}_6 = \frac{\begin{vmatrix} -2.1429 & 147.6263 \\ 1.2875 & -147.415 \end{vmatrix}}{\begin{vmatrix} -2.1429 & 2.4965 \\ 1.2875 & -0.1308 \end{vmatrix}} = \frac{125.826}{-2.9339}$$

$= -42.8869$ rad/sec (CCW)

Now substitute the respective (given and calculated) in the equations (9) & (10), and get the acceleration.

$$-2.5(\sin 59^0)\ddot{\theta}_5 + 2.5(\sin 87^0)\ddot{\theta}_6 = 2.5(-118.854)^2 \cos 59^0$$
$$- 1/2(2)(-195)^2(\cos 35^0) - 1/2(2)(49423.99)\sin 35^0$$
$$- 2.5(-42.8869)^2 \cos 87^0 - 1/2(2)(37.84059)^2(-\cos 109^0)$$
$$- 1/2(2)(129027.99)(-\sin 109^0)$$

$$2.5(\cos 59^0)\ddot{\theta}_5 - 2.5(\cos 87^0)\ddot{\theta}_6 = 2.5(-118.854)^2 \sin 59^0$$
$$- \tfrac{1}{2}(2)(-195)^2 \sin 35^0 - 1/2(2)(49423.99)\cos 35^0$$
$$+ 2.5(-42.8869)^2(-\sin 87^0) - 1/2(2)(37.84059)^2 \times$$
$$(-\sin 109^0) - 1/2(2)(129027.99)\cos 109^0$$

By Simplifying

$$-2.1429\,\ddot{\theta}_5 + 2.4965\,\ddot{\theta}_6 = 79983.753 \quad \text{——— (G)}$$
$$1.2875\,\ddot{\theta}_5 - 0.1308\,\ddot{\theta}_6 = 87716.357 \quad \text{——— (H)}$$

By Cramer's rule

$$\ddot{\theta}_5 = \frac{\begin{vmatrix} 79983.753 & 2.4965 \\ 87716.357 & -0.1308 \end{vmatrix}}{\begin{vmatrix} -2.1429 & 2.4965 \\ 1.2875 & -0.1308 \end{vmatrix}} = \frac{-229445.76}{-2.9339}$$

$= 78205.038$ rad/sec (CCW)

$$\ddot{\theta}_6 = \frac{\begin{vmatrix} -2.1429 & 79983.753 \\ 1.2875 & 87716.357 \end{vmatrix}}{\begin{vmatrix} -2.1429 & 2.4965 \\ 1.2875 & -0.13 0 8 \end{vmatrix}} = \frac{-290946.46}{-2.9339}$$

$$= 99167.137 \text{ rad/sec (ccw)}$$

The above analytical results are very close to the results obtained by DRAM. However there seems to be problem in the $\dot{\theta}_4$ result obtained by DRAM.

	ANALYTICAL RESULTS AN	DRAM RESULTS DR	PERCENTAGE DEVIATION. $\left\lvert\frac{AN-DR}{AN}\right\rvert \times 100$
Angular Velocity ($\dot{\theta}_3$) rad/sec.	−195	−197.2771	1.16
Angular Velocity ($\dot{\theta}_4$) rad/sec	37.84059	34.01955	*10.097
Angular velocity ($\dot{\theta}_5$) rad/sec	−118.854	−119.781	0.78
Angular Velocity ($\dot{\theta}_6$)	−42.8869	−43.4765	1.37
Angular Acceleration ($\ddot{\theta}_3$) rad/sec^2	49423.99	49418.4	0.011
Angular Acceleration ($\ddot{\theta}_4$) rad/sec	129027.99	130560.00	1.187
Angular Acceleration ($\ddot{\theta}_5$) rad/sec	78205.038	79546.7 00	1.71
Angular Acceleration ($\ddot{\theta}_6$) rad/sec	99167.137	100432.00	1.27

Table No. 3 : Comparison of Analytical Results with DRAM Results and % error.

* The result has an error and is difficult to trace.

EXAMPLE # A.4 Undamped Free Vibrations:

Given:-- $W_1 = W_2 = 50$ Lb.

$K_1 = 20$ Lb/inch, $K_2 = 15$ Lb/inch.

$L_1 = L_2 = 3$ inch.

Find :- Displacement velocity and acceleration of the given spring mass system.

Initial conditions:- $X_1(t) = 0$ when $t=0$

$X_2(t) = 0$ when $t=0$

$\dot{x}_1(t) = 25$ when $t=0$

$\dot{x}_2(t) = 25$ when $t=0$

Diagram :- Spring mass System.

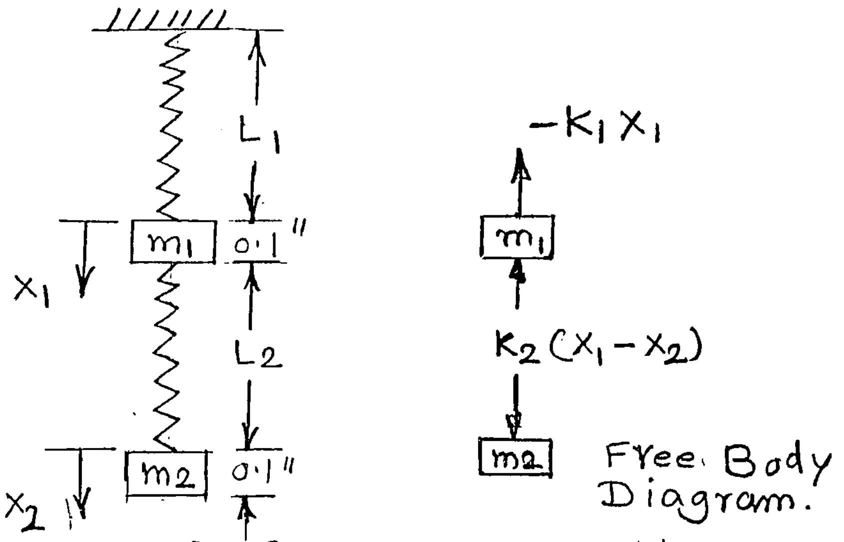


FIG. A.4 Spring Mass System

Equations Of Motion:-

Employing $\Sigma F = ma$ we have

$$m_1 \ddot{x}_1 = -k_1 x_1 - k_2(x_1 - x_2)$$

$$m_2 \ddot{x}_2 = -k_2(x_2 - x_1)$$

By rearranging the equations of motion, it follows that:

$$m_1\ddot{x}_1 + (k_2+k_1)x_1 - k_2x_2 = 0$$
$$m_2\ddot{x}_2 + k_2x_2 - k_2x_1 = 0$$

Assumption :- The motion is periodic

$$x_1 = A\sin(\omega t+\psi), \quad x_2 = B\sin(\omega t+\psi)$$

where A, B and ψ are arbitrary constants and ω one of the natural frequencies of the system. Let us calculate the values of $\dot{x}_1$ and $\dot{x}_2$, $\ddot{x}_1$ and $\ddot{x}_2$:

$$\dot{x}_1 = A\omega\cos(\omega t+\psi), \quad \dot{x}_2 = B\omega\cos(\omega t+\psi)$$
$$\ddot{x}_1 = -A\omega^2\sin(\omega t+\psi), \quad \ddot{x}_2 = -B\omega^2\sin(\omega t+\psi)$$

Substituting these values into the equations of motion we obtain

$$-m_1A\omega^2\sin(\omega t+\psi) + (k_1+k_2)A\sin(\omega t+\psi) - k_2B\sin(\omega t+\psi) = 0$$
$$-m_2B\omega^2\sin(\omega t+\psi) + k_2B\sin(\omega t+\psi) - k_2A\sin(\omega t+\psi) = 0$$

cancelling out $\sin(\omega t+\psi)$ throughout we get

$$(k_1+k_2-m_1\omega^2)A - k_2B = 0$$
$$-k_2A + (k_2-m_2\omega^2)B = 0$$

Thus $$\begin{vmatrix} k_1+k_2-m_1\omega^2 & -k_2 \\ -k_2 & k_2-m_2\omega^2 \end{vmatrix} = 0$$

By expanding the determinant, we have

$$\omega^4 - \left[\frac{k_1+k_2}{m_1} + \frac{k_2}{m_2}\right]\omega^2 + \frac{k_1k_2}{m_1m_2} = 0$$

which is the frequency equation of the system.

By Solving

$$\omega^2 = \frac{k_1+k_2}{2m_1} + \frac{k_2}{2m_2} \pm \sqrt{\frac{1}{4}\left[\frac{k_1+k_2}{m_1} + \frac{k_2}{m_2}\right]^2 - \frac{k_1k_2}{m_1m_2}}$$

The general solution of the equations of motion is composed of two harmonic motions of the frequencies w_1 and w_2. Therefore

$$x_1 = A_1 \sin(\omega_1 t + \psi_1) + A_2 \sin(\omega_2 t + \psi_2)$$

$$x_2 = B_1 \sin(\omega_1 t + \psi_1) + B_2 \sin(\omega_2 t + \psi_2)$$

where A's, B's and ψ's are arbitrary constants. The amplitude ratios are (calculed from the equation of motion)

$$\frac{A_1}{B_1} = \frac{K_2}{K_1 + K_2 - m_1 w_1^2} = \lambda_1 ; \quad \frac{A_2}{B_2} = \frac{K_2}{K_1 + K_2 - m_1 w_2^2} = \lambda_2$$

Hence, finally the general solution becomes:

$$x_1 = B_1 \lambda_1 \sin(\omega_1 t + \psi_1) + B_2 \lambda_2 \sin(\omega_2 t + \psi_2)$$

$$x_2 = B_1 \sin(w_1 t + \psi_1) + 1 \quad B_2 \sin(w_2 t + \psi_2)$$

In these equations, there are B_1, B_2, ψ_1, ψ_2 unknowns which are to be calculated by the four initial conditions. $x_1(0), x_2(0), \dot{x}_1(0), \dot{x}_2(0)$.

Analytical solution:-

Now natural frequency is :-

$$w^2 = \frac{K_1 + K_2}{2m_1} + \frac{K_2}{2m_2} \pm \sqrt{\frac{1}{4}\left[\frac{K_1 + K_2}{m_1} + \frac{K_2}{m_2}\right]^2 - \frac{K_1 K_2}{m_1 m_2}}$$

Let

$$A = \frac{K_1 + K_2}{2m_1} + \frac{K_2}{2m_2}$$

$$= \frac{m_2(K_1 + K_2) + m_1 K_2}{2 m_1 m_2}$$

$$= \frac{\cancel{m}(K_1 + K_2) + \cancel{m} K_2}{2 m \cancel{m}} \qquad \because m_1 = m_2 = m = \frac{W}{g}$$

$$A = \frac{K_1 + 2K_2}{2m}$$

$$= \frac{20 + 2 \times 15}{2 \times 0.1293} = 193.3488 \qquad \because K_1 = 20 \text{ lb/inch}, \; K_2 = 15 \text{ lb/inch}, \; m = 40/386.088 = 0.1293 \text{ lb-sec}^2/\text{in}$$

$$B = \pm\sqrt{\frac{1}{4}\left[\frac{k_1+k_2}{m_1}+\frac{k_2}{m_2}\right]^2 - \frac{k_1k_2}{m_1m_2}}$$

$$= \pm\sqrt{\frac{1}{4}\left[\frac{m_2(k_1+k_2)+m_1k_2}{m_1m_2}\right]^2 - \frac{k_1k_2}{m_1m_2}}$$

$$= \pm\sqrt{\frac{1}{4}\left[\frac{\cancel{m}(k_1+k_2)+\cancel{m}k_2}{m\cancel{m}}\right]^2 - \frac{k_1k_2}{mm}} \qquad \because m_1=m_2=m$$

$$= \pm\sqrt{\frac{1}{4}\left[\frac{k_1+2k_2}{m}\right]^2 - \frac{k_1k_2}{m^2}}$$

$$= \pm\sqrt{\frac{1}{4}\left[\frac{20+2\times15}{0.1293}\right]^2 - \frac{20\times15}{(0.1293)^2}}$$

$$= \pm\ 139.4258$$

$$\therefore\ \omega^2 = A + B$$

$$= 193.3488 \pm 139.4258$$

$$\therefore\ \omega_2^2 = 332.7746 \quad \therefore\ \omega_2 = 18.242111 \text{ rad/sec}$$

$$\omega_1^2 = 53.923 \quad \therefore\ \omega_1 = 7.3432282 \text{ rad/sec.}$$

Amplitude ratios are :-

$$\frac{A_2}{B_2} = \frac{k_2}{k_1+k_2-m_1\omega_2^2}$$

$$= \frac{15}{20+15-0.1293(332.7746)}$$

$$= -1.8685172$$

and

$$\frac{A_1}{B_1} = \frac{k_2}{k_1+k_2-m_1\omega_1^2}$$

$$= \frac{15}{20+15-0.1293(53.93)}$$

$$= 0.535183376$$

Let us now impose the initial conditions on the solutions of the equations of motion.

$$x_1 = A_1 \sin(\omega_1 t + \psi_1) + A_2 \sin(\omega_2 t + \psi_2)$$

$$x_2 = B_1 \sin(\omega_1 t + \psi_1) + B_2 \sin(\omega_2 t + \psi_2)$$

Displacement:—

At $t=0$ $x_1(0) = 0$

$$x_1 = 0 = A_1 \sin\psi_1 + A_2 \sin\psi_2$$

$$0 = 0.535183376 B_1 \sin\psi_1 - 1.8685172 B_2 \sin\psi_2 \quad \text{——(1)}$$

At $t=0$ $x_2(0) = 0$

$$x_2 = 0 = B_1 \sin\psi_1 + B_2 \sin\psi_2$$

$$\therefore \quad B_1 \sin\psi_1 = -B_2 \sin\psi_2$$

Substituting this value in the equation (1) we get

$$0 = -1.8685172 B_2 \sin\psi_2 - 0.535183376 B_2 \sin\psi_2$$

$$= -\sin\psi_2 \, B_2 (1.8685172 + 0.535183376)$$

$$\sin\psi_2 = 0$$

$$\psi_2 = 0$$

So also $\sin\psi_1 = 0$

$$\psi_1 = 0$$

$$\therefore \quad x_1 = 0.535183376 B_1 \sin(\omega_1 t) - 1.8685172 B_2 \sin(\omega_2 t)$$

&

$$x_2 = B_1 \sin(\omega_1 t) + B_2 \sin(\omega_2 t)$$

Velocity:—

$$\dot{x}_1 = A_1 \omega_1 \cos(\omega_1 t) + A_2 \omega_2 \cos(\omega_2 t)$$

$$\dot{x}_2 = B_1 \omega_1 \cos(\omega_1 t) + B_2 \omega_2 \cos(\omega_2 t)$$

At $t=0$ $\dot{x}_1(0) = 25$, $\dot{x}_1(0) = 25$

$$\dot{x}_1(0) = 25 = 0.535183376 B_1 \times 7.3432282 (1) - 1.8685172 \times B_2 \times 18.242111 (1)$$

$$\dot{x}_2(0) = 25 = 7.3432282 B_1 + 18.242111 B_2$$

$$B_1 = \frac{\begin{vmatrix} 25 & -34.085698 \\ 25 & 18.242111 \end{vmatrix}}{\begin{vmatrix} 3.9299736 & -34.085698 \\ 7.3432282 & 18.242111 \end{vmatrix}}$$

$$= \frac{+1308.1952}{321.99013}$$

$$= 4.0628426$$

$$B_2 = \frac{\begin{vmatrix} 3.9299736 & 25 \\ 7.3432282 & 25 \end{vmatrix}}{\begin{vmatrix} 3.9299736 & -34.085698 \\ 7.343292 & 18.242111 \end{vmatrix}}$$

$$= \frac{-85.331293}{321.99013}$$

$$= -0.26501214$$

$\therefore A_1 = 0.53518337 \quad B_1 = 2.743658$

$A_2 = -1.8685172 \quad B_2 = 0.49519426$

Let us calculate displacement, velocity & acceleration at $t = 0.0003$ sec.

Displacement –

$X_1 = 2.1743658 \times \sin(7.3432282 \times 0.0003) + 0.49531678 \sin(18.242111 \times 0.0003)$

$= 0.0075006$ inch

$\therefore X_1' =$ initial length of spring + increment $= 3 + 0.0075006$

$= 3.0075006$ inch

& $X_2' = 4.0628426 \sin(7.3432282 \times 0.0003) - 0.26501214 \sin(18.242111 \times 0.0003)$

$= +0.0075$ inch

$\therefore X_2' = 6.1 - 0.0075$

where Total length = Length of system + 2(length of mass) = 6.1 inches.

$x_2' = 6.1075$ inches.

velocity:-

$\dot{x}_1 = 2.1743658 \times 7.3432282 \times \cos(7.3432282 \times 0.0003)$
$\quad - 0.49519426 \times 18.242111 \cos(18.242111 \times 0.0003)$
$= 25.000079$ inch/sec.

$\dot{x}_2 = 4.0628426 \times 7.3432282 \cos(7.3432282 \times 0.0003)$
$\quad + 0.26508548 \times 18.242111 \cos(18.242111 \times 0.0003)$
$= 24.9999$ inch/sec.

Acceleration:-

$\ddot{x}_1 = -2.1743658\,(53.923) \sin(7.3432282 \times 0.0003)$
$\quad - 0.49519426\,(332.7746) \sin(18.242111 \times 0.0003)$

$= -1.1601146$ inch/sec^2

At $t=0$, DRAM considers acceleration $= 386.088$ inch/sec^2

So for the analytical solution, the acceleration must be 386.088 inch/sec^2 at $t=0$. Now at $t=0.0003$, the analytical solution becomes

$\ddot{x}_1 = 386.088 + (-1.1601146)$
$= 384.92789$. inch/sec^2

Similarly

$\ddot{x}_2 = -4.0628426\,(53.923) \sin(7.3432282 \times 0.0003)$
$\quad - 0.26501214\,(332.7746) \sin(18.242111 \times 0.0003)$
$= -0.96525292$

$\ddot{x}_2 = 386.088 + (-0.96525292)$
$= 385.12275$ inch/sec

	ANALYTICAL RESULTS A_N	DRAM RESULTS D_R	PERCENTAGE DEVIATION $\left\lvert \frac{A_N - D_R}{A_N} \right\rvert \times 100$
AT TIME $T = 0.0003$ SEC			
Displacement (x_1') inch	3.0075006	3.007530	0.00097
Displacement (x_2') inch	6.10750	6.10753	0.00049
Velocity ($\dot{x}_1$) inch/sec	25.000079	25.1159	0.46
Velocity ($\dot{x}_2$) inch/sec	24.9999	25.1161	0.46.
Acceleration ($\ddot{x}_1$) inch/sec^2	384.92789	384.9250	0.00075
Acceleration ($\ddot{x}_2$) inch/sec^2	385.12275	386.088	0.25

Tabe NO. 4 ; Comparison of Analytical Results with DRAM Results and % deviation.

EXAMPLE # : A.5 Forced vibration with damping.

Given. Weight $W = 40 lbs$.

Damping coefficient $C = 0.85$ lb-sec/inch

Spring constant $K = 50$ lb/inch.

Spring length $L = 2.5$ inches

Magnitude of excitation force =

$F_0 = 10$ lbs.

Frequency of excitation

Force $\omega = 15$ rad/sec.

Initial Conditions:-

$x(t) = 0$ when $t = 0$

$\dot{x}(t) = 4$ when $t = 0$

Find: Determine the amplitude of vibration, the desplacement and velocity of the vibrating system.

Diagram:-

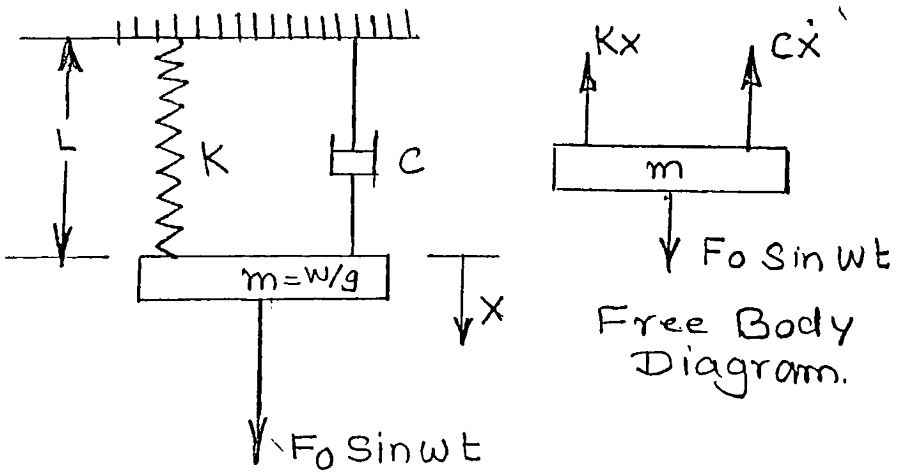
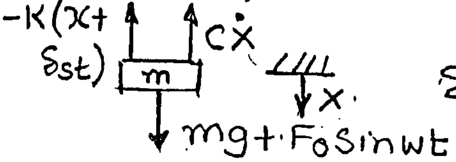


FIG. A5: Spring damper System

Equations of motion:-

Employing Newton's Law of motion.



$\Sigma M\ddot{x}$ = Sum of Forces in the x-direction

Force Dia. $\Sigma M\ddot{x} = -K(x+\delta_{st}) + mg - c\dot{x} + F_0 \sin \omega t$

where δ_{st} is a static deflection.

But $K\delta_{st} = mg$, the weight of man; hence the equation of motion takes its most general form

$$m\ddot{x} + c\dot{x} + Kx = F_0 \sin \omega t$$

The general solution for this second order differential equation with constant coefficients is

$$x = x_c + x_p$$

where x_c is the Complimentary solution
x_p is the Particular solution

We need to consider under damped vibration for the given problem since the damping Factor (ζ) is less than unity. Therefore

$$x_c = C e^{-\zeta \omega_n t} \sin(\omega_d t + \phi)$$ (Refer to Vibration Analysis by R. K. Vierck)

Where ω_d is the damped frequency, $\phi \rightarrow$ phase angle, ω_n is the natural frequency of vibration. and

$\omega_n = \sqrt{\frac{K}{m}}$ where $K \rightarrow$ spring constant & $m \rightarrow$ mass

$\omega_d = \omega_n \sqrt{1-\zeta^2}$ where $\zeta \rightarrow$ damping factor.

$$\zeta = \frac{c}{2mw_n} \quad \text{where } c \rightarrow \text{Damping coefficient.}$$

Now

$$x_p = \frac{F_o}{(k-mw^2)+(cw)^2} \sin(wt-\psi)$$ [Refer to Vibration Analysis by R. K. Vierck]

where $\psi = \tan^{-1}\frac{cw}{k-mw^2} = \tan^{-1}\frac{2\zeta(w/w_n)}{1-(w/w_n)^2}$

Therefore, the general solution becomes

$$x = ce^{-\zeta w_n t}\sin(w_d t+\phi) + E\sin(wt-\psi)$$

where E is a constant

Analytical Solution:-

$$m = W/g = \frac{40}{386.088} = 0.10360332 \text{ lbf-sec}^2/\text{inch}$$

$$w_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{50}{0.10360332}} = 21.968389 \text{ rad/sec}$$

$$\zeta = \frac{c}{2mw_n} = \frac{0.85}{2\times0.10360332\times21.968389}$$

$$= 0.1867327 \quad < 1 \quad \text{Underdamped.}$$

$$w_d = w_n\sqrt{1-\zeta^2} = 21.968389\sqrt{1-(0.1867327)^2}$$

$$= 21.581988 \text{ rad/sec.}$$

$$x_p = \frac{F_o}{\sqrt{(k-mw^2)^2+(cw)^2}} \sin(wt-\psi)$$

$$= \frac{10}{\sqrt{[50-0.10360332(15)^2]^2+(0.85\times15)^2}} \sin(15t-\psi)$$

$$= 0.3380851 \sin(15t-\psi)$$

$$\psi = \tan^{-1}\frac{c\omega}{K - m\omega^2} = \frac{0.85 \times 15}{50 - 0.10360332(15)^2}$$

$$= \tan^{-1} 0.47772038$$

$$= 25.534757^0 \qquad = 0.44566558 \text{ rad.}$$

Amplitude of vibration.

$$X_p = 0.3380851 \sin(15t - \psi)$$

$$= 0.3380851 \sin(15 \times 0.00003 - 0.44566558)$$

$X_p = -0.145597$ when $t = 0.00003$ sec.

$X_p = -0.145460$ when $t = 0.00006$ sec.

$X_p = -0.145323$ when $t = 0.00009$ sec.

Now

$$\zeta\omega_n = 0.18673127 \times 21.968389 = 4.1021852$$

$\therefore$ The general solution becomes

$$X = c e^{-4.1021852t} \sin(21.581988t + \phi) + 0.3380851 \sin(15t - 25.534757^0)$$

Let us impose the given initial conditions

$$X(t) = 0 \quad \text{at } t = 0$$

$$\therefore X(t) = 0 = c \sin\phi + 0.3380851 \sin(-25.534757^0)$$

$$\therefore c \sin\phi = 0.14573447 \qquad \text{——— (1)}$$

Now

$$\dot{X} = c(-4.1021852) e^{-4.1021852t} \sin(21.581988t + \phi)$$
$$+ c e^{-4.1021852t}\, 21.581988 \cos(21.581988t + \phi)$$
$$+ 0.3380851 \times 15 \cos(15t - 25.534757^0)$$

at $t=0$ $\quad \dot{x}(0)=4$

$$4 = C\left[-4.1021852\sin\phi + 21.581988\cos\phi\right] + 0.3380851\times 15\cos(-25.534757^\circ)$$

$$4 = C\sin\phi\left[-4.1021852 + 21.581988\frac{\cos\phi}{\sin\phi}\right] + 4.5759329$$

$$4 = 0.1457344\left[-4.1021852 + 21.581988\cot\phi\right] + 4.5759329$$

$$\cot\phi = \frac{0.0218968}{3.1452396}$$

$$\therefore \tan\phi = \frac{3.1452396}{0.0218968}$$

$$\therefore \phi = 89.60112^\circ = 1.5638346 \text{ rad.}$$

$$C\sin\phi = 0.14573447$$

$$C = \frac{0.14573447}{\sin 89.60112^\circ} = 0.145738$$

By imposing intial conditions, we have calculated the values of constant C and angle ϕ. Substitute these values in the general solution of the differential equation Therefore

$$X = 0.145738\, e^{-4.1021852t}\sin(21.581988t + 89.60112^\circ) + 0.3380851\sin(15t - 25.534757^\circ)$$

The velocity can be calculated by differentiating 'x' expression. So

$$\dot{X} = 0.145738\left\{(-4.1021852)\, e^{-4.1021852t}\sin(21.581988t + 89.60112^\circ) + e^{-4.1021852t}\, 21.581988\cos(21.581988t + 89.60112^\circ)\right\} + 0.33808\times 15\cos(15t - 25.534757^\circ)$$

Let us calculate the displacement, and velocity when $t = 0.00003$ sec.

Therefore

$$x = 0.145738\, e^{-4.1021852 \times 0.00003} \sin(21.581988 \times 0.00003 \times 1.56346)$$

$$+ 0.3380851 \sin(15 \times 0.00003 - 0.4456658)$$

$$= 0.00012 \text{ inch}$$

Total displacement = Initial length + Increment

$= 2.5 + 0.00012$

$= 2.50012$ inch.

&

$$\dot{x} = 0.145738 \left\{ (-4.1021582)\, e^{-4.1021852 \times 0.00003} \times \right.$$

$$\sin(21.581988 \times 0.00003 + 1.56346) \times$$

$$\left. e^{-4.1021852 \times 0.00003} \cos(21.581988 \times 0.00003 + 1.56346) \right\}$$

$$+ 0.3380851 \times 15 \cos(15 \times 0.00003 - 0.44566558)$$

$$= 3.999014 \text{ inch/sec}$$

Let us calculate the displacement and velocity again by considering two different time intervals.

Now at $t = 0.00006$ sec.

$$x = 0.145738\, e^{-4.102852 \times 0.00006} \sin(21.581988 \times 0.00006 + 1.56346)$$

$$+ 0.3380.851 \sin(15 \times 0.00006 - 0.44566558)$$

$$= 0.00024 \text{ inch.}$$

Total displacement = Initial length + Increment

$= 2.5 + 0.00024$

$= 2.50024$ inch.

& $\dot{x} = 0.145738\{(-4.1021582\, e^{-4.1021852 \times 0.00006} \times \sin(21.581988 \times 0.00006 + 1.56346)$

$+ e^{-4.1021582 \times 0.00006}\; 21.581988 \cos(21.581988 \times 0.00006 + 1.56346)\}$

$+ 0.3380851 \times 15 \cos(15 \times 0.00006 - 0.44566558)$

$= 3.998033$ inch/sec.

Similarly at $t = 0.00009$ sec.

$x = 0.00036$ inch

Total displacement = Initial length + increment

$= 2.5 + 0.00036$

$= 2.50036$ inch

$\dot{x} = 3.997050$ inch/sec.

ENTER COMMAND

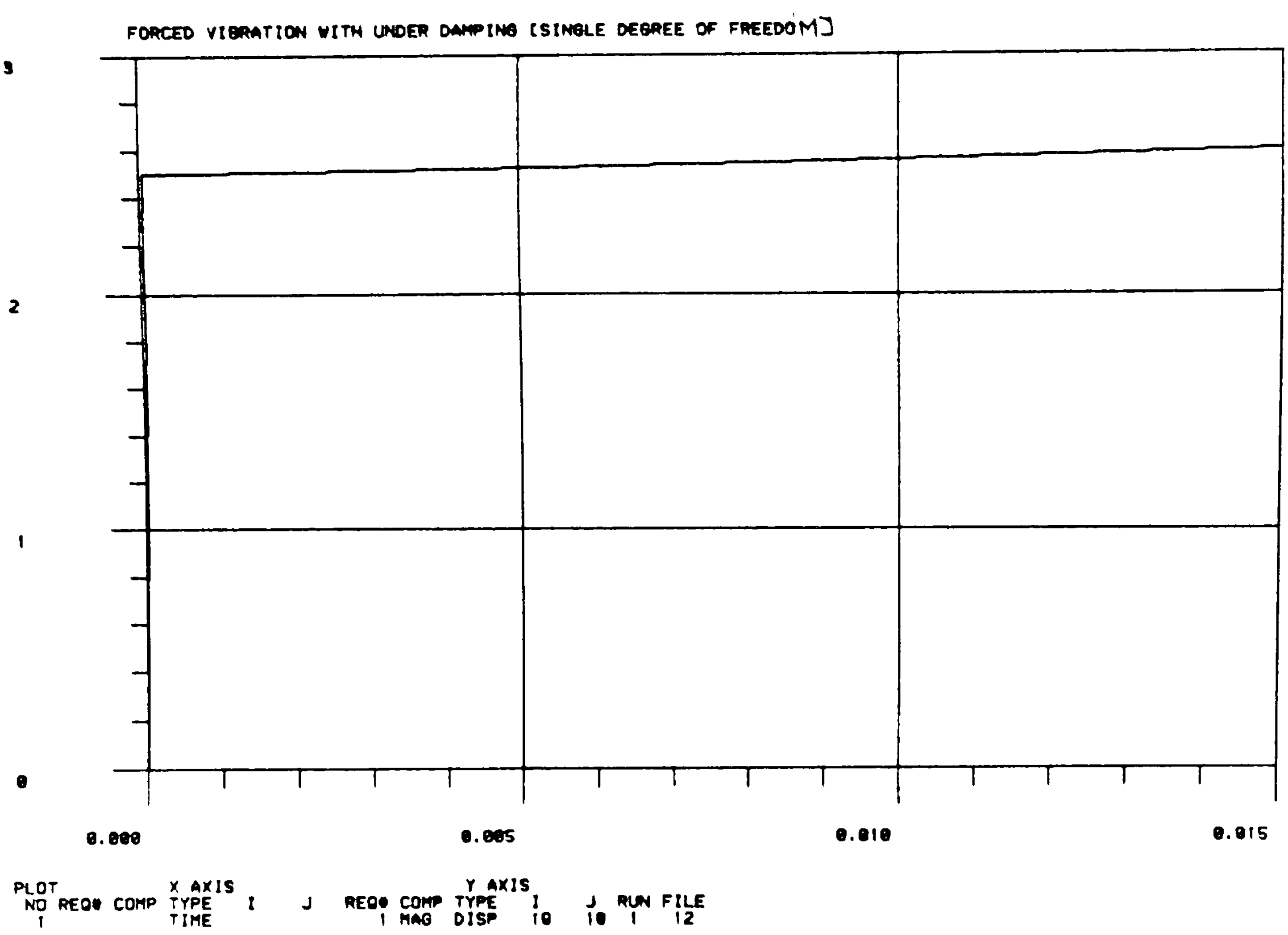


FIG. A 5.2 : DISPLACEMENT (DRAM).

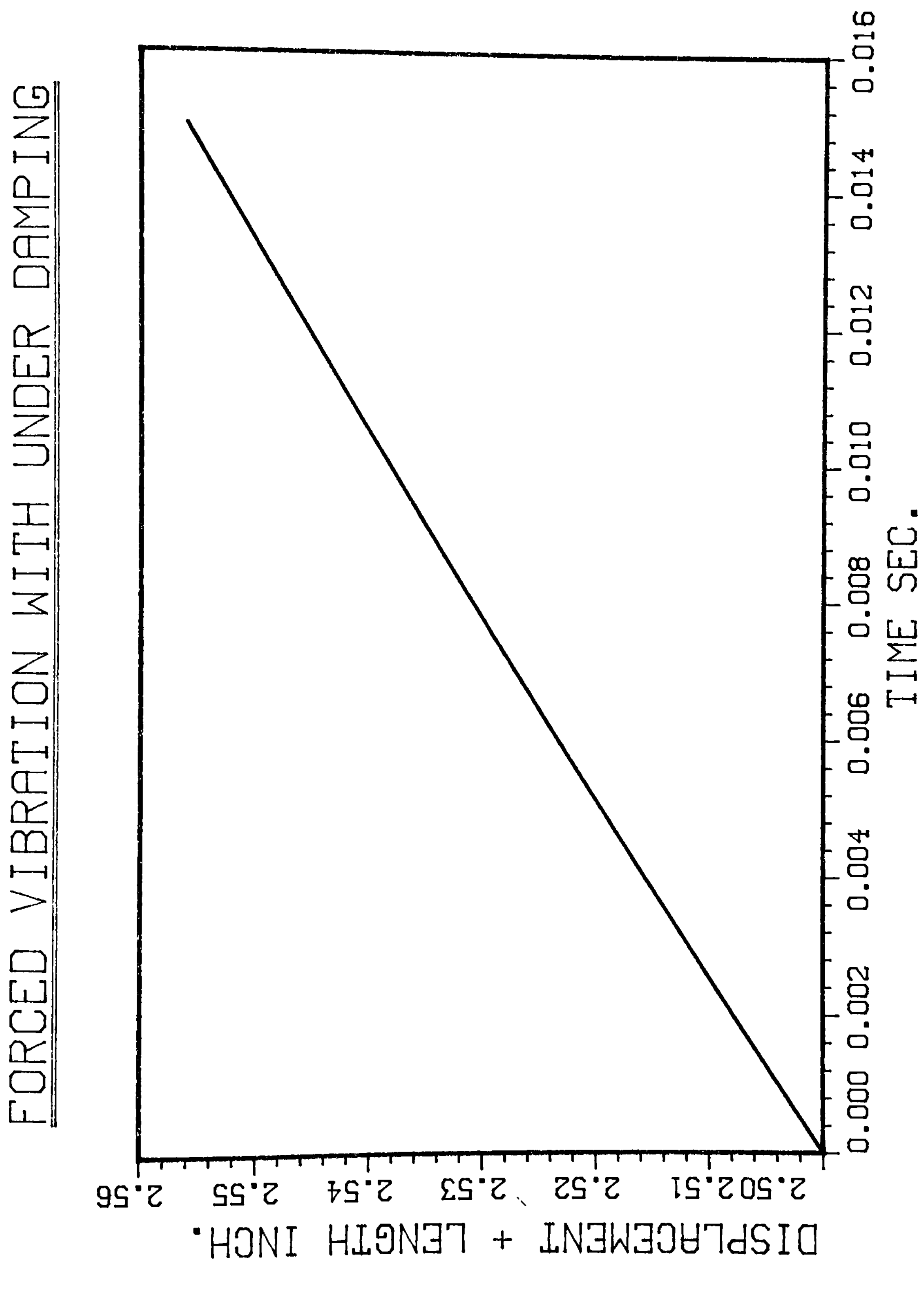


FIG. A5.3 : DISPLACEMENT (ANALYTICAL).

ENTER COMMAND

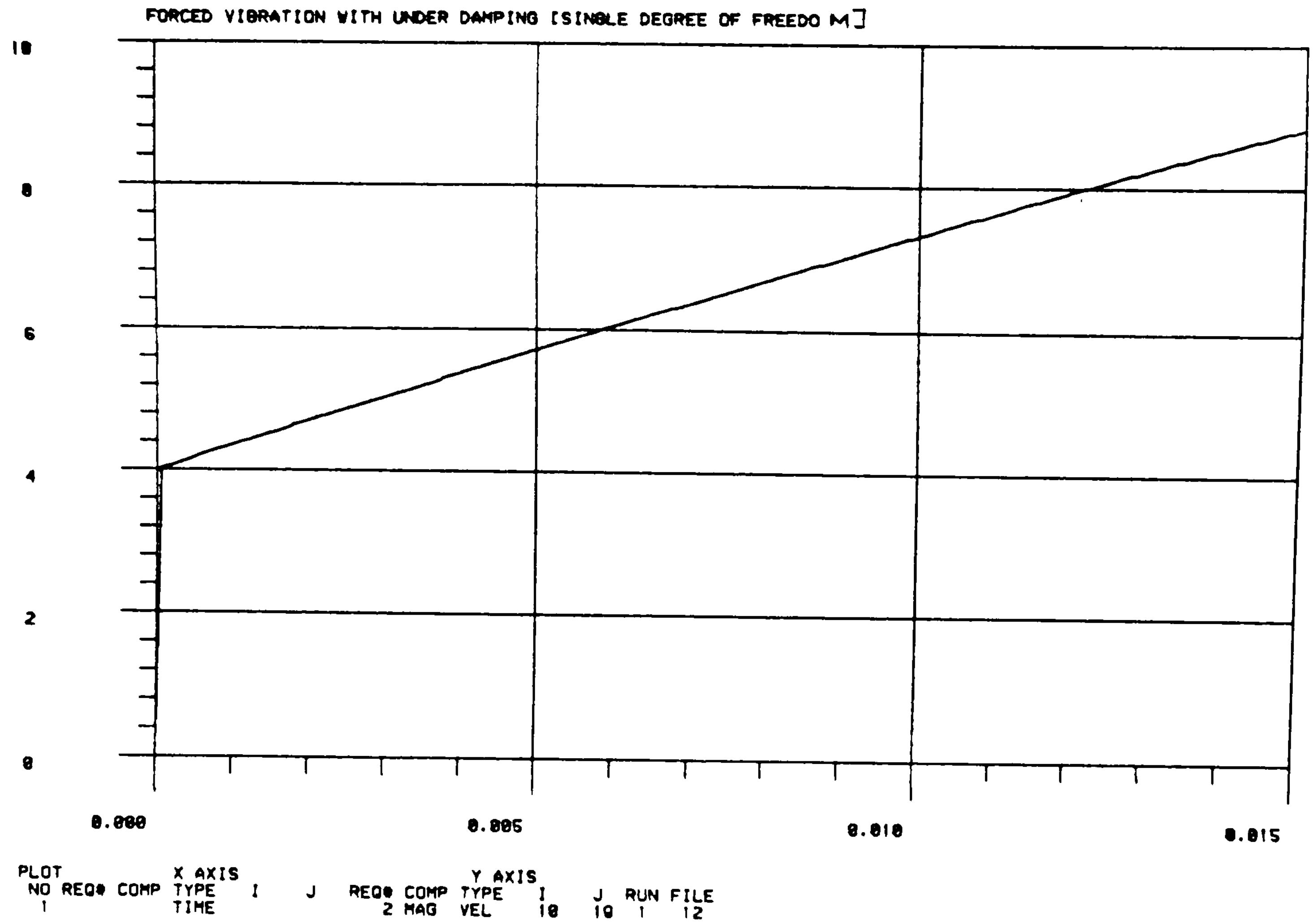


FIG. A5.4 : VELOCITY (DRAM).

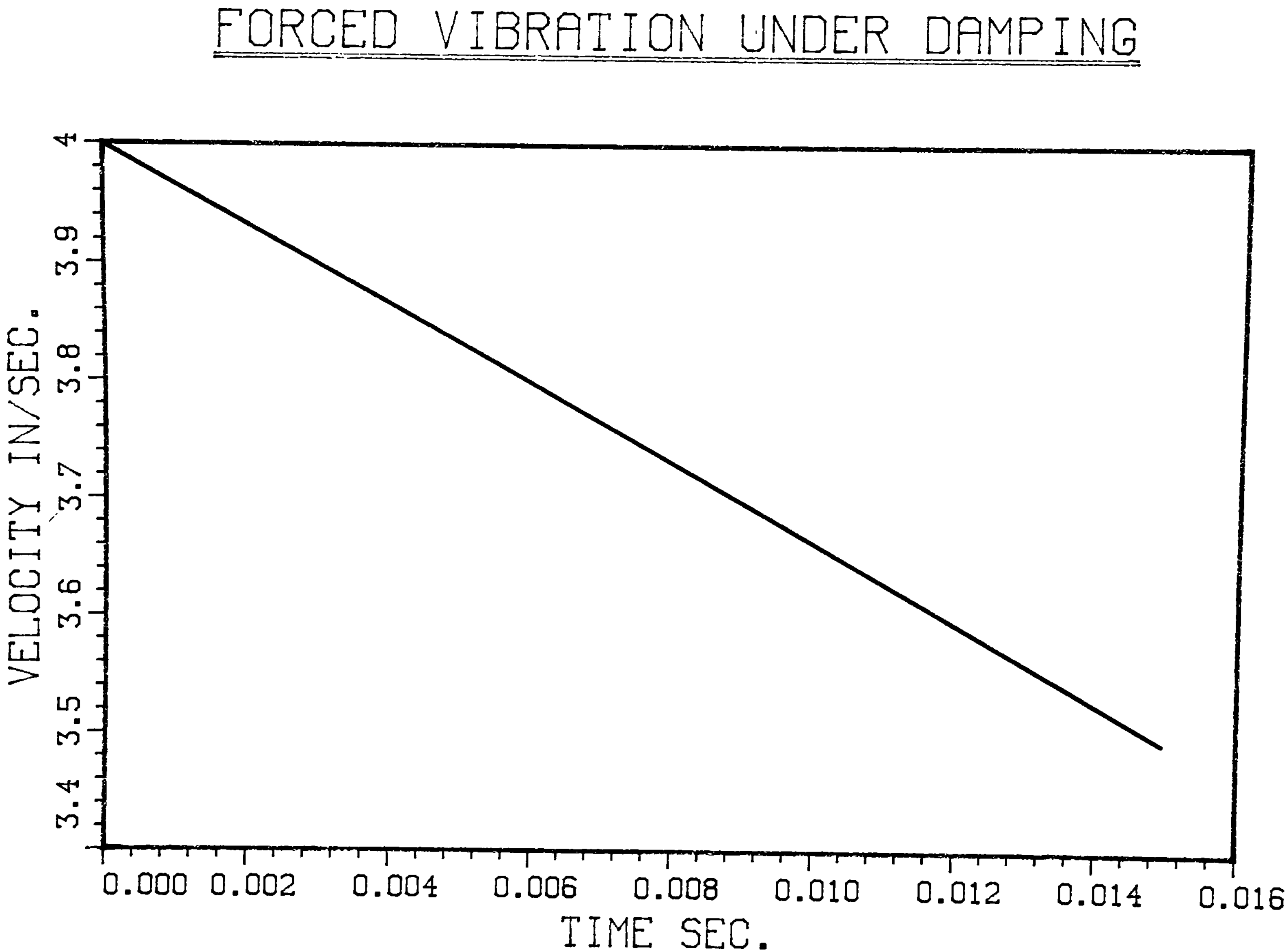
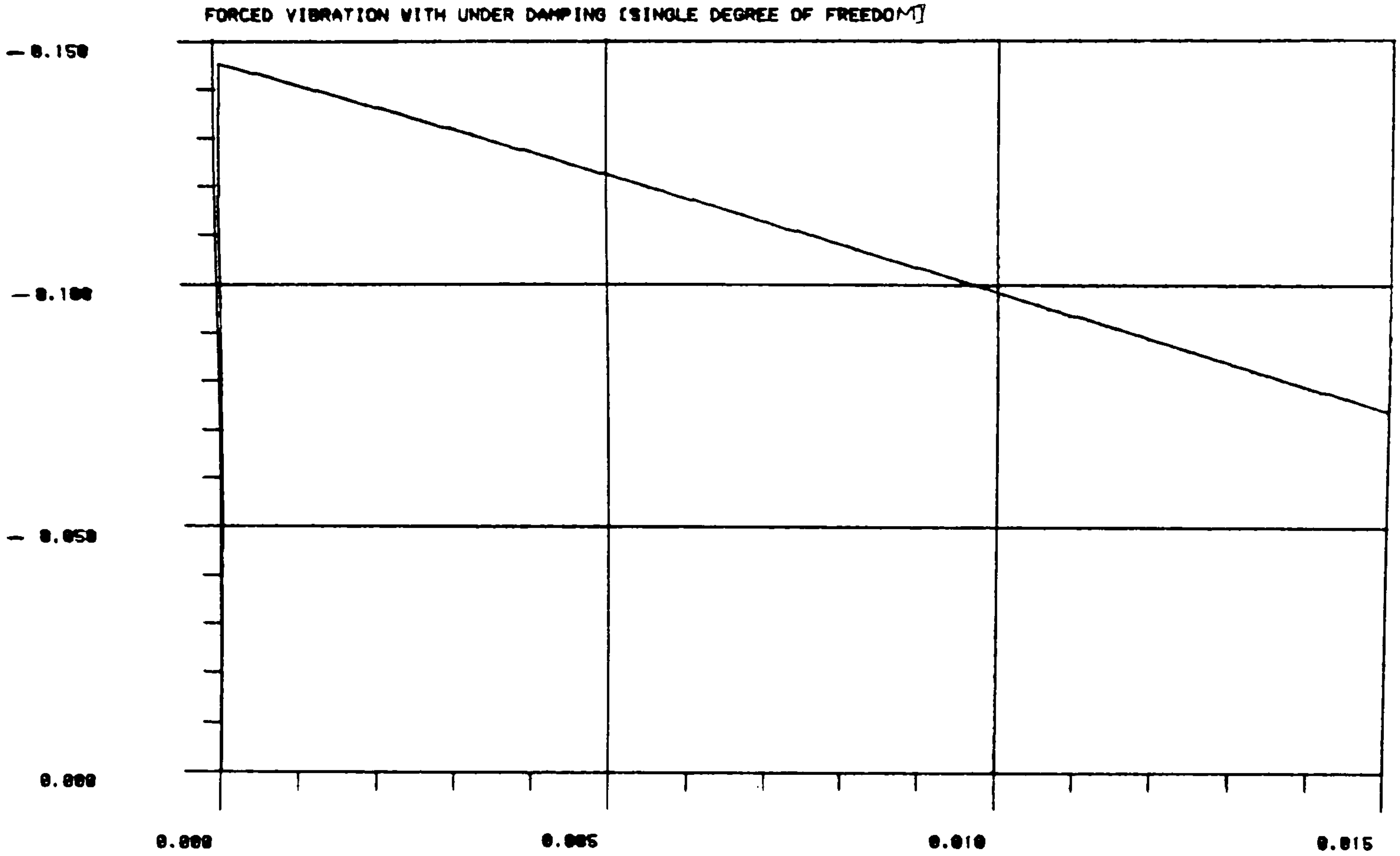


FIG. A 5.5: VELOCITY (ANALYTICAL).

ENTER COMMAND



PLOT X AXIS Y AXIS
NO REQ# COMP TYPE I J REQ# COMP TYPE I J RUN FILE
1 TIME MAG RSUB 1 12

FIG. A 5.6 : AMPLITUDE OF VIBRATION (DRAM).

FOECED VIBRATION WITH UNDER DAMPING

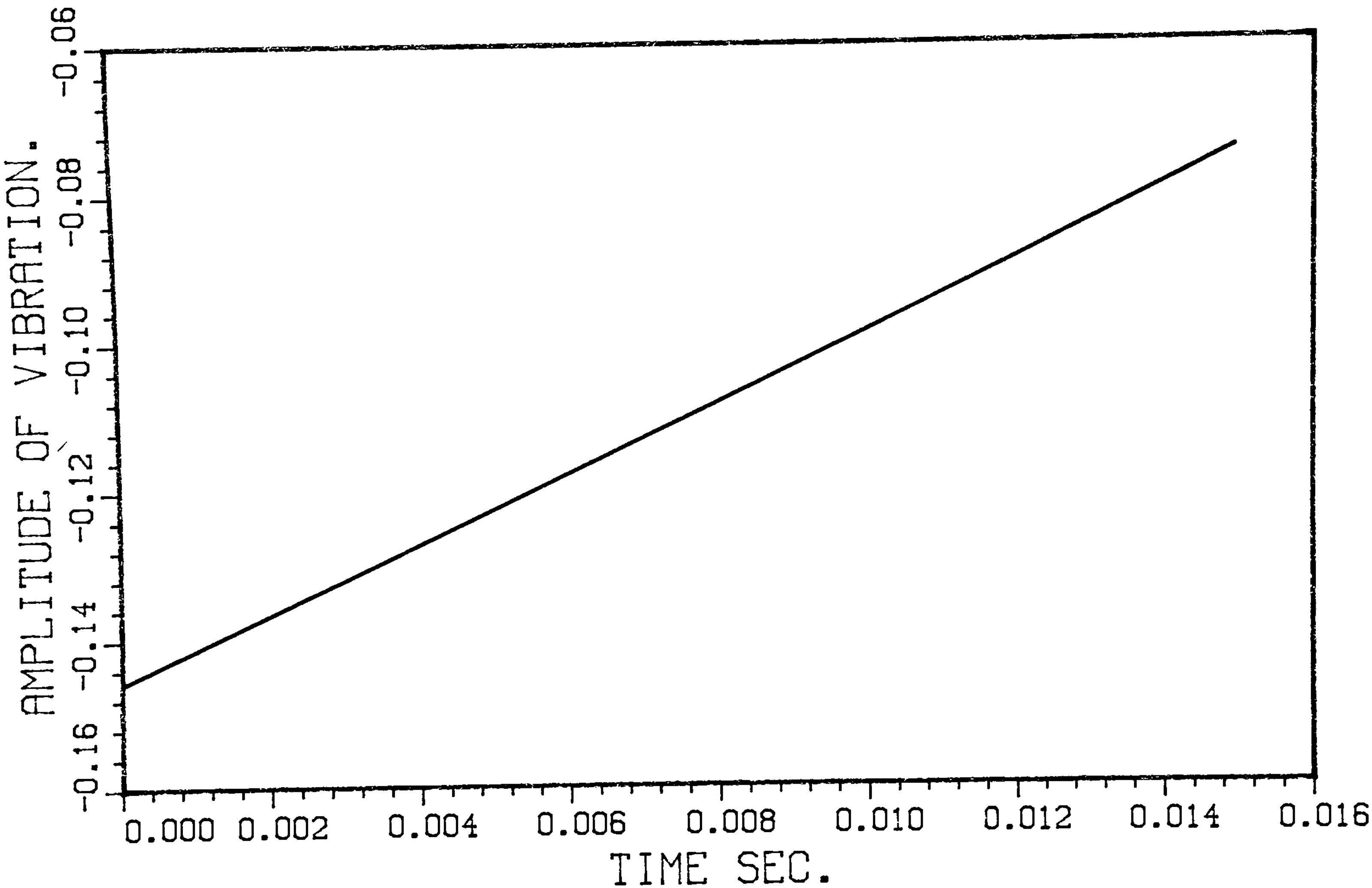


FIG. A 5.7 : AMPLITUDE OF VIBRATION (ANALYTICAL).

	ANALYTICAL RESULTS A_N	DRAM RESULTS D_R	PERCENTAGE DEVIATION $\left\lvert \frac{A_N - D_R}{A_N} \right\rvert \times 100$
At time t=0.00003 sec			
Displacement (x) inch	2.500120	2.50012	—
Velocity ($\dot{x}$) inch/sec	3.999014	4.01062	0.29
Amplitude of vibration	-0.145597	-0.145597	—
At time t=0.00006 sec.			
Displacement (x) inch	2.50024	2.50024	-
velocity ($\dot{x}$) inch/sec	3.998033	4.02121	0.57
Amplitude of Vibration	-0.145460	-0.145460	-
At time t=0.00009 sec.			
Displacement (x) inch	2.50036	2.50036	—
Velocity ($\dot{x}$) inch/sec	3.997050	4.03180	0.86
Amplitude of Vibration	-0.145323	-0.145322	-

Table NO. 5 : Comparison of Analytical Results with DRAM Results and % deviation.

Comments:

This example is an important one since it shows that DRAM results for forced response can deviate quite drastically from an analytical solution, as time increases from t=0. It was necessary to control the deviation by reducing significantly the end time of the forced response, and increasing the number of steps for the DRAM solution. This was accomplished by changing the END value on the OUTPUT statement from 0.3 to 0.015, and STEPS from 300 to 500. Note that the DRAM results in figure A 5.2 are scaled differently from the analytical results presented in figure A 5.3. The same comments applies to the velocity and amplitude of vibration. It is apparent from Table No. 5 that both techniques agree well for a small time interval. Figures A 5.2 to A 5.7, however, show that large discrepancies arise as time increases. Mechanical Dynamic Inc., the supplier for DRAM, acknowledges that this is a common difficulty when DRAM is applied to forced vibration problems.

```
* PROGRAMMER      : DEEPAK N. RODE
*
* DATE WRITTEN    : DECEMBER 17, 1987
*
* OBJECTIVE       : TO FIND THE DISPLACEMENT, VELOCITY AND
*                   AMPLITUDE OF THE FORCED VIBRATION OF THE
*                   MECHANICAL SYSTEM.
*
*        MAXN   -  MAXIMUM NUMBER OF STEPS.
*        M      -  MASS OF THE SYSTEM.
*        WN     -  NATURAL FREQUENCY OF VIBRATION.
*        J      -  DAMPING FACTOR.
*        WD     -  DAMPED FREQUENCY.
*        E      -  CALCULATED CONSTANT VALUE.
*        W      -  FREQUENCY OF EXCITATION.
*        T      -  TIME.
*        CI     -  ANGLE CI.
*        PHI    -  ANGLE PHI.
*        XP     -  AMPLITUDE OF VIBRATION.
*        X      -  DISPLACEMENT.
*        X1     -  VELOCITY.
* WORK VARIABLE :
*
*        C1,C2,A,B,PHI1,PHI2,C,WD1,XC1,XP1
*
*
         REAL*4 M,WN,J

         LOGICAL*1 SUCCESS

          MAXN = 500
             M = 0.10360332
            WN = 21.968389
            J  = 0.1867327
            WD = 21.581988
             E = 0.3380851
             W = 15.0
             T = 0.0
*
         WRITE (6,15)
 15      FORMAT(12X,'TIME',14X,'X',14X,'X1',14X,'XP',/)

         DO 10 K=1,MAXN

            C1 = 50.0-(0.10360332*(15.0)**2)
            C2 = 0.85*15
            CI = ATAN2D(C2,C1)
*
             A = 15.0*T*180.0/3.1415927
*
            XP = (0.3380851)*SIND(A-CI)
*
             B = J*WN
*
          PHI1 = 3.1452396
          PHI2 = 0.0218968
           PHI = ATAN2D(PHI1,PHI2)
             C = 0.14573447/SIND(PHI)

*        DISPLACEMENT............
```

```
      WD1 = WD*T*180.0/3.145927
        X = (C*EXP(-B*T))*SIND(WD1+PHI)+E*SIND(A-CI)
        X = X+2.5

*        VELOCITY................

      XC1 = (C*(-B)/(2.71828183)**(B*T))*SIND(WD1+PHI)
     / +(C*WD/((2.71828183)**(B*T)))*COSD(WD1+PHI)
      XP1 = E*W*COSD(A-CI)
       X1 = XC1+XP1

        WRITE(6,20) T,X,X1,XP
*        WRITE(6,20)T,XP

20      FORMAT(2X,11(1X,F15.6))

              T = T+0.00003

10      END DO

        SUCCESS= .TRUE.

        END
```

TIME	X	X1	XP
0.000000	2.500000	3.999996	-0.145734
0.000030	2.500120	3.999014	-0.145597
0.000060	2.500240	3.998033	-0.145460
0.000090	2.500360	3.997050	-0.145323
0.000120	2.500480	3.996068	-0.145185
0.000150	2.500600	3.995086	-0.145048
0.000180	2.500720	3.994102	-0.144910
0.000210	2.500839	3.993120	-0.144773
0.000240	2.500959	3.992137	-0.144635
0.000270	2.501079	3.991153	-0.144498
0.000300	2.501199	3.990170	-0.144360
0.000330	2.501318	3.989186	-0.144223
0.000360	2.501438	3.988202	-0.144085
0.000390	2.501558	3.987218	-0.143947
0.000420	2.501677	3.986234	-0.143810
0.000450	2.501797	3.985249	-0.143672
0.000480	2.501916	3.984265	-0.143534
0.000510	2.502036	3.983280	-0.143396
0.000540	2.502155	3.982294	-0.143259
0.000570	2.502275	3.981310	-0.143121
0.000600	2.502394	3.980324	-0.142983
0.000630	2.502513	3.979339	-0.142845
0.000660	2.502633	3.978353	-0.142707
0.000690	2.502752	3.977367	-0.142569
0.000720	2.502872	3.976381	-0.142431
0.000750	2.502991	3.975395	-0.142293
0.000780	2.503110	3.974408	-0.142155
0.000810	2.503229	3.973421	-0.142017
0.000840	2.503348	3.972435	-0.141879
0.000870	2.503468	3.971447	-0.141741
0.000900	2.503587	3.970460	-0.141603
0.000930	2.503706	3.969473	-0.141465
0.000960	2.503825	3.968485	-0.141327
0.000990	2.503944	3.967497	-0.141188
0.001020	2.504063	3.966510	-0.141050
0.001050	2.504182	3.965521	-0.140912
0.001080	2.504301	3.964533	-0.140774
0.001110	2.504420	3.963544	-0.140635
0.001140	2.504539	3.962556	-0.140497
0.001170	2.504658	3.961567	-0.140358
0.001200	2.504776	3.960578	-0.140220
0.001230	2.504895	3.959589	-0.140082
0.001260	2.505014	3.958599	-0.139943
0.001290	2.505133	3.957610	-0.139805
0.001320	2.505251	3.956620	-0.139666
0.001350	2.505370	3.955630	-0.139527
0.001380	2.505489	3.954640	-0.139389
0.001410	2.505607	3.953650	-0.139250
0.001440	2.505726	3.952660	-0.139112
0.001470	2.505845	3.951670	-0.138973
0.001500	2.505963	3.950678	-0.138834
0.001530	2.506082	3.949688	-0.138696
0.001560	2.506200	3.948697	-0.138557
0.001590	2.506319	3.947706	-0.138418
0.001620	2.506437	3.946714	-0.138279
0.001650	2.506555	3.945722	-0.138140
0.001680	2.506674	3.944731	-0.138001
0.001710	2.506792	3.943739	-0.137863

FORCED VIBRATION WITH UNDER DAMPING [SINGLE DEGREE OF FREEDOM]

REQUEST NUMBER 1

TIME	MAGNITUDE OF THE LINEAR DISPLACEMENT OF MARKER 19 RELATIVE TO MARKER 10	ANGLE (RADIANS)	MAGNITUDE OF THE ANGULAR DISPLACEMENT (RADS) OF MARKER 19 RELATIVE TO MARKER 10
0.0000E+00	2.50000E+00	4.71239E+00	-1.57080E+00
3.0000E-05	2.50012E+00	4.71239E+00	-1.57080E+00
6.0000E-05	2.50024E+00	4.71239E+00	-1.57080E+00
9.0000E-05	2.50036E+00	4.71239E+00	-1.57080E+00
1.2000E-04	2.50048E+00	4.71239E+00	-1.57080E+00
1.5000E-04	2.50060E+00	4.71239E+00	-1.57080E+00
1.8000E-04	2.50073E+00	4.71239E+00	-1.57080E+00
2.1000E-04	2.50085E+00	4.71239E+00	-1.57080E+00
2.4000E-04	2.50097E+00	4.71239E+00	-1.57080E+00
2.7000E-04	2.50109E+00	4.71239E+00	-1.57080E+00
3.0000E-04	2.50122E+00	4.71239E+00	-1.57080E+00
3.3000E-04	2.50134E+00	4.71239E+00	-1.57080E+00
3.6000E-04	2.50146E+00	4.71239E+00	-1.57080E+00
3.9000E-04	2.50159E+00	4.71239E+00	-1.57080E+00
4.2000E-04	2.50171E+00	4.71239E+00	-1.57080E+00
4.5000E-04	2.50184E+00	4.71239E+00	-1.57080E+00
4.8000E-04	2.50196E+00	4.71239E+00	-1.57080E+00
5.1000E-04	2.50209E+00	4.71239E+00	-1.57080E+00
5.4000E-04	2.50221E+00	4.71239E+00	-1.57080E+00
5.7000E-04	2.50234E+00	4.71239E+00	-1.57080E+00
6.0000E-04	2.50246E+00	4.71239E+00	-1.57080E+00
6.3000E-04	2.50259E+00	4.71239E+00	-1.57080E+00
6.6000E-04	2.50272E+00	4.71239E+00	-1.57080E+00
6.9000E-04	2.50284E+00	4.71239E+00	-1.57080E+00
7.2000E-04	2.50297E+00	4.71239E+00	-1.57080E+00
7.5000E-04	2.50310E+00	4.71239E+00	-1.57080E+00
7.8000E-04	2.50323E+00	4.71239E+00	-1.57080E+00
8.1000E-04	2.50336E+00	4.71239E+00	-1.57080E+00
8.4000E-04	2.50348E+00	4.71239E+00	-1.57080E+00
8.7000E-04	2.50361E+00	4.71239E+00	-1.57080E+00
9.0000E-04	2.50374E+00	4.71239E+00	-1.57080E+00
9.3000E-04	2.50387E+00	4.71239E+00	-1.57080E+00
9.6000E-04	2.50400E+00	4.71239E+00	-1.57080E+00
9.9000E-04	2.50413E+00	4.71239E+00	-1.57080E+00
1.0200E-03	2.50426E+00	4.71239E+00	-1.57080E+00
1.0500E-03	2.50439E+00	4.71239E+00	-1.57080E+00
1.0800E-03	2.50453E+00	4.71239E+00	-1.57080E+00
1.1100E-03	2.50466E+00	4.71239E+00	-1.57080E+00
1.1400E-03	2.50479E+00	4.71239E+00	-1.57080E+00
1.1700E-03	2.50492E+00	4.71239E+00	-1.57080E+00
1.2000E-03	2.50505E+00	4.71239E+00	-1.57080E+00
1.2300E-03	2.50519E+00	4.71239E+00	-1.57080E+00
1.2600E-03	2.50532E+00	4.71239E+00	-1.57080E+00
1.2900E-03	2.50545E+00	4.71239E+00	-1.57080E+00
1.3200E-03	2.50559E+00	4.71239E+00	-1.57080E+00
1.3500E-03	2.50572E+00	4.71239E+00	-1.57080E+00
1.3800E-03	2.50586E+00	4.71239E+00	-1.57080E+00
1.4100E-03	2.50599E+00	4.71239E+00	-1.57080E+00
1.4400E-03	2.50612E+00	4.71239E+00	-1.57080E+00
1.4700E-03	2.50626E+00	4.71239E+00	-1.57080E+00
1.5000E-03	2.50640E+00	4.71239E+00	-1.57080E+00

FORCED VIBRATION WITH UNDER DAMPING [SINGLE DEGREE OF FREEDOM]

REQUEST NUMBER 2

TIME	MAGNITUDE OF THE LINEAR VELOCITY OF MARKER 10 RELATIVE TO MARKER 19	ANGLE (RADIANS)	MAGNITUDE OF THE ANGULAR VELOCITY (RAD) OF MARKER 10 RELATIVE TO MARKER 19
0.0000E+00	4.00000E+00	1.57080E+00	0.00000E+00
3.0000E-05	4.01062E+00	1.57080E+00	0.00000E+00
6.0000E-05	4.02121E+00	1.57080E+00	0.00000E+00
9.0000E-05	4.03180E+00	1.57080E+00	0.00000E+00
1.2000E-04	4.04239E+00	1.57080E+00	0.00000E+00
1.5000E-04	4.05297E+00	1.57080E+00	0.00000E+00
1.8000E-04	4.06355E+00	1.57080E+00	0.00000E+00
2.1000E-04	4.07413E+00	1.57080E+00	0.00000E+00
2.4000E-04	4.08471E+00	1.57080E+00	0.00000E+00
2.7000E-04	4.09528E+00	1.57080E+00	0.00000E+00
3.0000E-04	4.10585E+00	1.57080E+00	0.00000E+00
3.3000E-04	4.11642E+00	1.57080E+00	0.00000E+00
3.6000E-04	4.12698E+00	1.57080E+00	0.00000E+00
3.9000E-04	4.13754E+00	1.57080E+00	0.00000E+00
4.2000E-04	4.14809E+00	1.57080E+00	0.00000E+00
4.5000E-04	4.15865E+00	1.57080E+00	0.00000E+00
4.8000E-04	4.16920E+00	1.57080E+00	0.00000E+00
5.1000E-04	4.17975E+00	1.57080E+00	0.00000E+00
5.4000E-04	4.19029E+00	1.57080E+00	0.00000E+00
5.7000E-04	4.20083E+00	1.57080E+00	0.00000E+00
6.0000E-04	4.21137E+00	1.57080E+00	0.00000E+00
6.3000E-04	4.22190E+00	1.57080E+00	0.00000E+00
6.6000E-04	4.23244E+00	1.57080E+00	0.00000E+00
6.9000E-04	4.24297E+00	1.57080E+00	0.00000E+00
7.2000E-04	4.25349E+00	1.57080E+00	0.00000E+00
7.5000E-04	4.26401E+00	1.57080E+00	0.00000E+00
7.8000E-04	4.27453E+00	1.57080E+00	0.00000E+00
8.1000E-04	4.28505E+00	1.57080E+00	0.00000E+00
8.4000E-04	4.29556E+00	1.57080E+00	0.00000E+00
8.7000E-04	4.30607E+00	1.57080E+00	0.00000E+00
9.0000E-04	4.31658E+00	1.57080E+00	0.00000E+00
9.3000E-04	4.32708E+00	1.57080E+00	0.00000E+00
9.6000E-04	4.33758E+00	1.57080E+00	0.00000E+00
9.9000E-04	4.34808E+00	1.57080E+00	0.00000E+00
1.0200E-03	4.35857E+00	1.57080E+00	0.00000E+00
1.0500E-03	4.36906E+00	1.57080E+00	0.00000E+00
1.0800E-03	4.37955E+00	1.57080E+00	0.00000E+00
1.1100E-03	4.39004E+00	1.57080E+00	0.00000E+00
1.1400E-03	4.40052E+00	1.57080E+00	0.00000E+00
1.1700E-03	4.41100E+00	1.57080E+00	0.00000E+00
1.2000E-03	4.42147E+00	1.57080E+00	0.00000E+00
1.2300E-03	4.43194E+00	1.57080E+00	0.00000E+00
1.2600E-03	4.44241E+00	1.57080E+00	0.00000E+00
1.2900E-03	4.45288E+00	1.57080E+00	0.00000E+00
1.3200E-03	4.46334E+00	1.57080E+00	0.00000E+00
1.3500E-03	4.47380E+00	1.57080E+00	0.00000E+00
1.3800E-03	4.48425E+00	1.57080E+00	0.00000E+00
1.4100E-03	4.49471E+00	1.57080E+00	0.00000E+00
1.4400E-03	4.50515E+00	1.57080E+00	0.00000E+00
1.4700E-03	4.51560E+00	1.57080E+00	0.00000E+00
1.5000E-03	4.52604E+00	1.57080E+00	0.00000E+00

FORCED VIBRATION WITH UNDER DAMPING [SINGLE DEGREE OF FREEDOM]

REQUEST NUMBER 3

**** RSUB REQUEST ****

TIME	AMPLITUDE OF VIBRATION		
0.0000E+00	-1.45734E-01	0.00000E+00	0.00000E+00
3.0000E-05	-1.45597E-01	0.00000E+00	0.00000E+00
6.0000E-05	-1.45460E-01	0.00000E+00	0.00000E+00
9.0000E-05	-1.45322E-01	0.00000E+00	0.00000E+00
1.2000E-04	-1.45185E-01	0.00000E+00	0.00000E+00
1.5000E-04	-1.45047E-01	0.00000E+00	0.00000E+00
1.8000E-04	-1.44910E-01	0.00000E+00	0.00000E+00
2.1000E-04	-1.44773E-01	0.00000E+00	0.00000E+00
2.4000E-04	-1.44635E-01	0.00000E+00	0.00000E+00
2.7000E-04	-1.44498E-01	0.00000E+00	0.00000E+00
3.0000E-04	-1.44360E-01	0.00000E+00	0.00000E+00
3.3000E-04	-1.44222E-01	0.00000E+00	0.00000E+00
3.6000E-04	-1.44085E-01	0.00000E+00	0.00000E+00
3.9000E-04	-1.43947E-01	0.00000E+00	0.00000E+00
4.2000E-04	-1.43809E-01	0.00000E+00	0.00000E+00
4.5000E-04	-1.43672E-01	0.00000E+00	0.00000E+00
4.8000E-04	-1.43534E-01	0.00000E+00	0.00000E+00
5.1000E-04	-1.43396E-01	0.00000E+00	0.00000E+00
5.4000E-04	-1.43258E-01	0.00000E+00	0.00000E+00
5.7000E-04	-1.43121E-01	0.00000E+00	0.00000E+00
6.0000E-04	-1.42983E-01	0.00000E+00	0.00000E+00
6.3000E-04	-1.42845E-01	0.00000E+00	0.00000E+00
6.6000E-04	-1.42707E-01	0.00000E+00	0.00000E+00
6.9000E-04	-1.42569E-01	0.00000E+00	0.00000E+00
7.2000E-04	-1.42431E-01	0.00000E+00	0.00000E+00
7.5000E-04	-1.42293E-01	0.00000E+00	0.00000E+00
7.8000E-04	-1.42155E-01	0.00000E+00	0.00000E+00
8.1000E-04	-1.42017E-01	0.00000E+00	0.00000E+00
8.4000E-04	-1.41879E-01	0.00000E+00	0.00000E+00
8.7000E-04	-1.41741E-01	0.00000E+00	0.00000E+00
9.0000E-04	-1.41603E-01	0.00000E+00	0.00000E+00
9.3000E-04	-1.41465E-01	0.00000E+00	0.00000E+00
9.6000E-04	-1.41326E-01	0.00000E+00	0.00000E+00
9.9000E-04	-1.41188E-01	0.00000E+00	0.00000E+00
1.0200E-03	-1.41050E-01	0.00000E+00	0.00000E+00
1.0500E-03	-1.40912E-01	0.00000E+00	0.00000E+00
1.0800E-03	-1.40773E-01	0.00000E+00	0.00000E+00
1.1100E-03	-1.40635E-01	0.00000E+00	0.00000E+00
1.1400E-03	-1.40497E-01	0.00000E+00	0.00000E+00
1.1700E-03	-1.40358E-01	0.00000E+00	0.00000E+00
1.2000E-03	-1.40220E-01	0.00000E+00	0.00000E+00
1.2300E-03	-1.40081E-01	0.00000E+00	0.00000E+00
1.2600E-03	-1.39943E-01	0.00000E+00	0.00000E+00
1.2900E-03	-1.39804E-01	0.00000E+00	0.00000E+00
1.3200E-03	-1.39666E-01	0.00000E+00	0.00000E+00
1.3500E-03	-1.39527E-01	0.00000E+00	0.00000E+00
1.3800E-03	-1.39389E-01	0.00000E+00	0.00000E+00
1.4100E-03	-1.39250E-01	0.00000E+00	0.00000E+00
1.4400E-03	-1.39111E-01	0.00000E+00	0.00000E+00
1.4700E-03	-1.38973E-01	0.00000E+00	0.00000E+00
1.5000E-03	-1.38834E-01	0.00000E+00	0.00000E+00
1.5300E-03	-1.38695E-01	0.00000E+00	0.00000E+00

EXAMPLE # A.6 Stephenson's Kinematic Chain.

This problem has been selected from the research paper "Analysis of Angular velocities and Acceleration in Plane Linkages by Means of Numerical Procedure". This paper has been published in ASME Journal of Mechanisms, Transmission, and Automation in Design, December 1983, Vol. 105/627.

The analytical results are also disclosed in this paper. All calculated results from the DRAM can be compared with the analytical results.

Given :-

Lengths :-

$\bar{r}_2 = 1.6$ inches, $\bar{r}_3 = 4.5$ inches

$\bar{r}_4 = 4.5$ inches $\bar{r}_4' = 2.1$ inches

$\bar{r}_4'' = 3.2$ inches, $\bar{r}_5 = 2.4$ inches

$\bar{r}_6 = 4.0$ inches, $\bar{r}_1 = 4.8$ inches

$\bar{r}_1' = 3.4$ inches, $\bar{r}_1'' = 1.8$ inches.

Angles :-

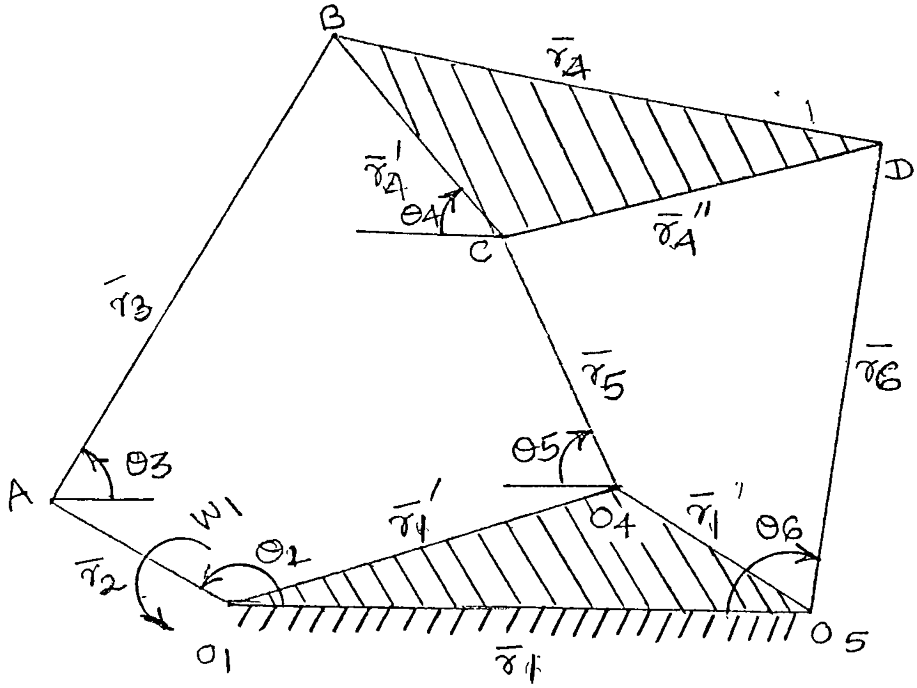
$\theta_2 = 150^0$, $\theta_3 = 60^0$

$\theta_4 = -45^0$, $\theta_5 = -65^0$, $\theta_6 = -97^0$

$\dot{\theta}_2 = 436.3$ rad/sec (CCW) constant

Find: Determine the angular velocities and angular accelerations of the kinematic system.

Diagram:- Stephonson's kinematic chain



RESULT CHART (COMPARISM)

	NUMERICAL RESULTS	DRAM RESULTS	PERCENTAGE DEVIATION $\left\|\frac{AN-DR}{AN}\right\| \times 100$
At $\theta_2 = 150^0$			
Velocity (Angular) $\dot{\theta}_3$ rad/sec	89.8172	87.9028	2.13
$\dot{\theta}_4$ rad/sec	108.2970	110.7950	2.30
$\dot{\theta}_5$ rad/sec	243.7909	236.5684	2.96
$\dot{\theta}_6$ rad/sec	156.2524	154.4671	1.14
Acceleration (Angular)			
$\ddot{\theta}_3$ rad/sec^2	28455	29433.4	3.43
$\ddot{\theta}_4$ rad/sec^2	-575	-989.00	*71.47
$\ddot{\theta}_5$ rad/sec^2	-26544	-26126.5	1.57
$\ddot{\theta}_6$ rad/sec^2	23983	23306.6	2.82

Table NO. 6 : Comparison of Analytical Results with DRAM Results.

* Note that the ASME paper employs a numerical technique, and this deviation is difficult to trace.